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Metamorphism of Granite Rocks by Olivine Dolerite in Central Australia

By ALLAN F. WILSON

ABSTRACT

A zone of intense metamorphism extends for six feet on both sides of a nearly vertical fifteen feet wide olivine dolerite dyke. Adamellites have been converted in situ to rocks resembling quartz porphyries, and mobilization of cordierite gneiss has been effected. Petrography and chemical analyses show that metamorphism is not purely thermal. Although little actual fixation of doleritic " end liquors " took place in the wall rocks the cause of these remarkable contact effects is ascribed to hydrothermal activity near the " blind end " of the dyke.

INTRODUCTION

IN the Kulgera Hills, about 160 miles south-south-west of Alice Springs, in Central Australia, certain (?) Pre-Cambrian olivine dolerites, the last manifestation of igneous activity in this region, have had an unusual and profound contact effect upon granitic rocks. In the case selected for description a zone of intense metamorphism extends for about 6 feet on both sides of a nearly vertical 15 feet wide olivine dolerite dyke.

Since this discovery (in December, 1948) the writer has seen in Western Australia other examples of comparable metamorphism. One occurs 2 miles south of Williams, on the Albany Highway, and another is 2 miles west of York, on the Perth–York road.

PETROGRAPHY

A. *Olivine dolerite* (No. 30103) [1]

This specimen was collected about 3 feet from the western edge of a north–south nearly vertical dyke which is about 15 feet wide and intrusive into the granitic complex ¾ mile north-north-east of Kulgera Hill. The contacts are sharp, there is no evidence of shearing or shattering of the wall rocks, and there is some diminution in grain size in the dyke toward the contacts. In hand-specimen it is a typical dark grey non-porphyritic dolerite.

[1] All numbers refer to specimens housed in the University of Western Australia, but duplicates are in the collection of the University of Adelaide.

The mode (by volume) is: plagioclase 41·8, end-phase 14·2, pyroxene 35·5, olivine 4·9, magnetite 3·6.

Thin section study shows that the minerals are remarkably fresh notwithstanding the large percentage of end-phase. Plagioclase laths (length about 1 mm.) occur in typical ophitic relation to the clinopyroxenes. Plagioclase is zoned—the inner two-thirds by volume is bytownite of fairly constant composition (about An_{82-80}). This core gives way to a selvage of gradationally zoned plagioclase with average composition near andesine (An_{43}) which, in turn, gives way rapidly through oligoclase into an acidic end-phase, the base of which is an oligoclase (about An_{20}) with a little albite. The end-phase feldspars are invariably charged with slender colourless apatite needles and subhedral magnetite. Some potash is fixed in occasional shreds of biotite (X = greenish-yellow, $Y = Z$ = brownish-green) but a dull yellowish-green chlorite is more abundant than biotite.

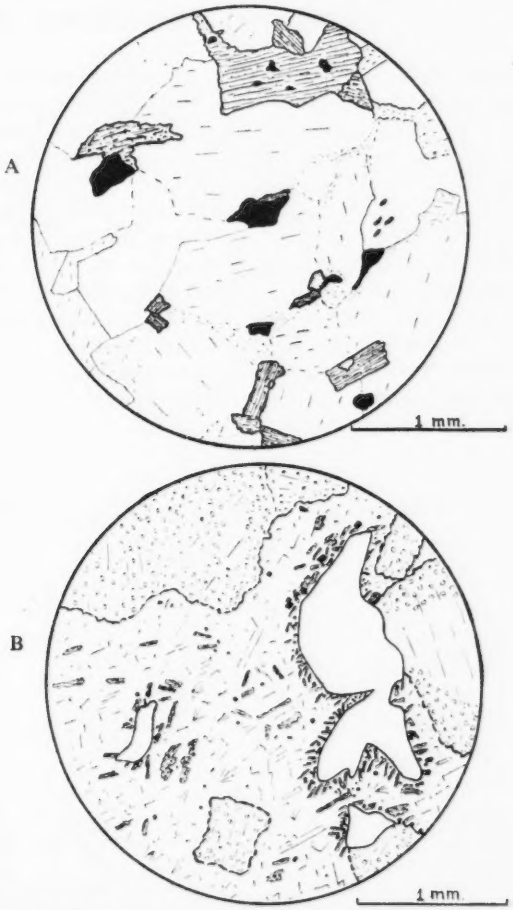
An unusual feature of this olivine dolerite is the presence of a little colourless calcite and clear quartz as the two last substances to crystallize in the end-phase. Since no potash feldspar was noticed it is remarkable that no sodic amphibole occurs as corrosive rims on pyroxene adjoining the patches of end-phase. Calculation of the norm indicated the presence of both hypersthene and augite, but careful study of both thin sections and heavy mineral fraction has failed to reveal any orthopyroxene. Two clinopyroxenes, however, are present (these are augite and (late) pigeonite).

Augite is very faint green, and pleochroic only near the edges. ($X = Z$ = pale aquamarine, Y = very faint rusty pink). Average grain size is 0·75 mm. 2V(+ ve) ranges from 52° in some cases, through 48° (common) to 40° in the more ferriferous edges. Late pigeonite occurs as occasional ophitic wedges or larger masses associated with the acidic end-phase. Its pleochroism is similar to, but more intense than, that of the ferro-augite selvages, and it has a somewhat greater birefringence. It is mostly uniaxial positive. Olivine occurs in clear colourless subhedra and is altered to orange-green serpentine only where in contact with the acidic end-phase. $2V = (-)85°$ suggests the olivine is chrysolite (Fa 35 mol %). The mineral is subhedral with average grain size 0·6 mm., and often enclosed in ophitic plates of augite. Neither ilmenite nor pyrite occur, and the only iron ore is subhedral magnetite which crystallized toward the end of pyroxene crystallization and in the acidic end-phase.

A chemical analysis of the rock appears in Table I.

B. *Metamorphism*

Though contacts with the granitic complex are always sharp and neither shattered nor sheared, there is a zone of marked metamorphism



TEXT-FIG. 1.—Textures of unaltered and hornfelsed micro-adamellite.

A. Typical texture of *unaltered micro-adamellite*, No. 30101. Minerals shown are quartz (white), feldspar (andesine and microcline—faint cleavage and slightly kaolinized), biotite (well cleaved and stippled), magnetite (black), zircon (four rounded crystals included in quartz) and apatite (associated with biotite).

B. Typical texture of *hornfelsed micro-adamellite*, No. 30102, the result of contact metamorphism of A. Quartz (white) is corroded, and rimmed with ragged flakes of biotite (cleaved) and octahedra of magnetite (black). Original andesine has been largely converted to antiperthite (large poorly cleaved masses with small irregular patches of potash feldspar). Groundmass is composed of potash feldspar and quartz (often occurring as microgranophyre), sodic plagioclase, biotite and magnetite.

about 6 feet wide on both sides of the nearly vertical olivine dolerite, No. 30103.

The dolerite has caused comparable metamorphism of three types of country rock, viz. micro-adamellite, the (coarse) Kulgera adamellite, and cordierite gneiss. Each rock type has been converted into a dull greasy brown fine-grained rock resembling a quartz porphyry, the "phenocrysts" representing relics of quartz and (occasionally) plagioclase which have not suffered complete recrystallization (see Text-fig. 1). Specimens were collected from all three rock types at various known distances from the contact. The difficulty of ensuring chemical similarity sufficient for comparative study of possible metasomatism in the cordierite gneisses led the writer to concentrate his attention on the changes effected in the granites. Of the two granites the remarkable uniformity in chemical composition of the micro-adamellite especially commended itself for detailed petrographic and chemical analysis (see Table I).

TABLE I.—ANALYSES

	A	B	C	Into C *	Out of C	Approx. % Change
SiO_2	49·09	67·28	67·78	0·43	—	1*
Al_2O_3	14·92	16·02	15·72	—	0·28	2
Fe_2O_3	1·81	1·71	0·90	—	0·81	47
FeO	8·85	3·06	3·59	0·53	—	17*
MnO	0·18	0·13	0·12	—	—	—
MgO	11·27	1·42	1·36	—	0·06	4
CaO	10·16	3·08	2·48	—	0·60	19
Na_2O	1·62	2·96	3·17	0·21	—	7*
K_2O	0·48	3·68	3·66	—	—	—
H_2O+	0·22	0·24	0·66	0·42	—	175*
H_2O-	0·09	Nil	Nil	—	—	—
TiO_2	0·62	0·44	0·43	—	—	—
P_2O_5	0·09	0·09	0·07	—	—	—
CO_2	0·68	0·15	0·17	—	—	—
Total	100·08	100·26	100·11	—	—	—

A. Olivine dolerite (No. 30103), three-quarters of a mile N.N.E. Kulgera Hill, Kulgera Hills, Central Australia. *Anal.*: W. H. Herdsman.

B. Biotite micro-adamellite (No. 30101), 12 feet from contact of olivine dolerite (A). *Anal.*: W. H. Herdsman.

C. Hornfelsed micro-adamellite (No. 30102), one foot from contact of olivine dolerite (A). This is metamorphosed equivalent of (B). *Anal.*: W. H. Herdsman.

Consequently only brief descriptions are given of rocks other than the micro-adamellite.

1. *Metamorphism of Micro-adamellite.*

A fine even-grained biotite micro-adamellite occurs as a vertical dyke 3 feet wide cutting cordierite-sillimanite gneisses. It appears to

be remarkably uniform in character along the dyke except where it is cut by the olivine dolerite dyke.

(*a*) *Unaltered Micro-adamellite* (No. 30101).—This rock was collected 12 feet from the western contact (footwall). In hand-specimen is seen a slight flow layering of biotite (which is parallel to the walls of the dyke) and there is a general pink colour due to the prominent pink microcline crystals (about 1·5 mm. × 1·0 mm.). Plagioclase is colourless, quartz colourless and glassy, and biotite dull black.

In thin section the rock is found to have allotriomorphic granular texture with 40 per cent andesine (An_{39}), 25 per cent quartz, 20 per cent microcline, and 9 per cent biotite as the essential minerals. The biotite is pleochroic with X = straw yellow, $Y = Z$ = nearly opaque brownish-black. Magnetite, muscovite, zircon, monazite, and apatite are accessories. The average grain size diameter is about 1 mm. (see Text-fig. 1 A).

Though this rock appeared to be unaltered in the field, thin section shows that biotite has some dusty inclusions of secondary magnetite and a minor development of chlorite. The chemical analysis and norm of this rock appear in Tables I and II respectively.

TABLE II.—NORMS

	A	B	C	Into C *	Out of C	Approx. % Change
Qu	—	26·41	26·53	0·12	—	1*
Or	2·84	21·68	21·68	—	—	—
Ab	13·68	25·15	26·72	1·57	—	6*
An	31·97	13·26	10·20	—	3·06	23
Cor	—	2·27	2·78	0·51	—	22*
Di Wo	5·57	—	—	—	—	—
Di En	3·48	—	—	—	—	—
Di Fs	1·74	—	—	—	—	—
Hy En	19·55	3·55	3·40	—	0·15	4
Hy Of	9·74	3·70	5·35	1·65	—	45*
Ol Fo	3·61	—	—	—	—	—
Ol Fa	2·00	—	—	—	—	—
Mt	2·55	2·55	1·39	—	1·16	45
Il	1·22	0·84	0·84	—	—	—
Ap	0·20	0·34	0·34	—	—	—
Calc	1·60	0·40	0·40	—	—	—
Water	0·31	0·24	0·66	0·42	—	175*
Total	100·06	100·39	100·29	—	—	—
S.G.	3·04					
C.I.P.W. Classification	III, 5, 4, 4 Auvergnose	I, 4, 2, 3 Toscanose				

Index to A, B, and C—see Table I.

(*b*) *Hornfelsed Micro-adamellite* (No. 30102).—This rock was taken from a similar position within the same dyke as No. 30101 but only 1 foot from the dolerite contact. Hand-specimen shows an almost unbelievable metamorphism by the dolerite. The micro-adamellite is probably best described as a hornfels with a uniform dull greasy-brown colour, but it strongly resembles a quartz-plagioclase porphyry. Examination in thin section shows that the rock is composed of ragged relics (diameter 1–1·5 mm.) of plagioclase and quartz set in a fine even-grained groundmass of alkali-feldspars, quartz, biotite, and magnetite. The groundmass comprises about 60 per cent of the rock and has an average grain size diameter of 0·1 mm. (see Text-fig. 1 B).

The andesine individuals (An_{39}) are usually clear and unaltered at their centres, but a broad irregular rim ($\frac{1}{2}$ to $\frac{2}{3}$ by volume) of micro-antiperthite is developed where there is an intimate association of potash feldspar and host plagioclase. Original quartz has been strongly corroded and grotesquely shaped relics occur rimmed with biotite and potash feldspar laths. Original microcline seems to be absent but a potash feldspar ($2V = (-)80°$ suggests non-twinned microcline) is plentiful in the groundmass where it occurs intimately associated with tiny granules and wisps of quartz as micro-granophyre. Clear sodic plagioclase (strongly zoned from calcic oligoclase to albite) is abundant as sub-rectangular crystals and is free from either quartz or potash feldspar inclusions. Biotite is plentiful as ragged laths about 0·2 mm. long. It is strongly pleochroic with X = pale greenish-yellow, Z = khaki green, but this is variable, as more intense browns occur when in contact with iron ores. Colourless muscovite is a rare accessory in the groundmass. Magnetite occurs as tiny euhedra throughout the groundmass, as irregular relics or as mossy aggregates resulting from disintegration of original biotite. Zircon, monazite, and apatite are rare residual subhedra. Chlorite is not common, and only occasional small patches of calcite occur. The chemical analysis and norm appear in Tables I and II respectively.

2. *Metamorphism of Coarse Biotite-hornblende Adamellite.*

The unaltered adamellite in the vicinity of the dyke cannot be readily distinguished from the type Kulgera adamellite (No. 30138) from Kulgera Hill, $\frac{1}{6}$ mile due west.

(*a*) *Unaltered Coarse Biotite-hornblende Adamellite* (No. 30138)—*the Kulgera Adamellite.*—In hand-specimen this rock is a coarse even-grained rock with an overall pink colour. Average grain size diameter is about 5 mm. Minerals visible in hand-specimen are flesh-coloured microcline, dull white plagioclase (with occasional phenocrysts of bluish-grey plagioclase, 3 cm. × 1 cm.), shiny black biotite, dull black hornblende, and plentiful accessory brown sphene.

In thin section this rock is found to have a coarse allotriomorphic granular texture. Plagioclase (38 per cent) is oligoclase (An_{25}), and often occurs as corroded relics within the microcline (24 per cent) which shows good cross-hatch twinning and irregularly developed patches of micro-perthite. Quartz (23 per cent) shows strain shadows. The femic minerals biotite, hornblende, magnetite, sphene, apatite, and zircon tend to be concentrated in " basic clots ".

(*b*) *Hornfelsed Coarse Biotite-hornblende Adamellite* (No. 30112).—This rock is the Kulgera adamellite collected only 9 inches from the bottom contact of the dolerite dyke (compare 30113). Only some of the pink microcline may still be seen in hand-specimen as its place has been largely taken by a dull greasy-brown lithoidal groundmass. The plagioclase content seems to be comparable with the unaltered rock but no ferromagnesians can be recognized.

Thin section study shows that metamorphic phenomena are similar to those described in the hornfelsed micro-adamellite, No. 30102. Additional significant features are as follows :—

(1) The quartz-potash feldspar micrographic intergrowths are more prominent and many fields are typical granophyre.

(2) Where quartz occurs as (previously) rounded granules in microcline, it is invariably rimmed and corroded by a broad band of very fine micropegmatite.

(3) Only a few clusters of magnetite octahedra remain to mark the probable positions of original biotite and hornblende. A new biotite, similar to that described in No. 30102, has been formed.

(4) Sphene is only slowly corroded by the groundmass.

(5) Apatite and zircon remain unchanged.

(6) Groundmass has average grain size diameter of 0·2 mm. and comprises 40 per cent of the rock.

(*c*) *Hornfelsed Coarse Biotite-hornblende Adamellite* (No. 30113).—This rock is the Kulgera adamellite collected about 9 inches from the *top* contact of the dolerite dyke (compare No. 30112). In hand-specimen the rock has the appearance of a few irregular partly digested " xenoliths " of granite set in a dull dark grey lithoidal groundmass which comprises 80 per cent of the rock.

Thin section shows the groundmass to be fine grained (average 0·1 mm.) and granophyric. The processes described in No. 30112 have been carried further in this rock, but it should be noted that there is still no field or microscopic evidence of crushing or mobilization of this rock.

(*d*) *Hornfelsed Coarse Biotite-hornblende Adamellite* (No. 30114).—This rock is the most intensely metamorphosed equivalent of the Kulgera adamellite. It occurs one chain north from No. 30113 along the *top* junction of the dolerite dyke.

In hand-specimen it looks remarkably like a quartz-feldspar porphyry, but careful inspection shows that the " phenocrysts " are corroded relics of plagioclase and quartz set in a dull brownish-grey lithoidal hornfels groundmass which comprises 90 per cent of the rock.

Thin section study shows the average diameter of the feldspathic constituents of the groundmass to be about 0·1 mm. Apatite and zircon remain unaltered, but small euhedra of sphene in the groundmass seem to indicate that the anhedral masses of sphene in the parent rock are capable of recrystallization under the prevailing metamorphic conditions.

3. *Metamorphism of Cordierite-sillimanite Gneiss.*

Contorted cordierite-sillimanite gneisses and granitic gneisses of sedimentary origin are cut by the dolerite dyke. Three specimens were collected at 15 feet, 3 feet, and 1 foot respectively along the strike of a suitable gneissic band, and therefore should have been reasonably comparable in original chemical composition and texture.

(*a*) *Unaltered Cordierite-sillimanite Gneiss* (No. 30106).—This rock was collected 15 feet along the strike east of the dolerite. In hand-specimen alternating bands of pink microcline and colourless quartz, and of greasy black cordierite and shiny black biotite can be distinguished.

In thin section the cordierite ($2V = (+)85$, dispersion very weak $r > v$) is found to be fresh and colourless, and contains zircons surrounded by prominent pleochroic haloes. It occurs as rounded crystals in irregular bands interleaved with patches of quartz, microcline, and clear andesine. Bunches of sillimanite needles are included in several cordierite individuals. Biotite (X = fawn yellow, Z = dark khaki-brown) is a plentiful accessory. Magnetite is plentiful as irregular masses in the cordierite bands, and a small octahedra near the edges of biotite. The average grain size diameter is about 1·2 mm.

(*b*) *Hornfelsed Cordierite Gneiss* (No. 30107).—This rock was collected 3 feet from the eastern edge of the dolerite dyke (and thus 12 feet from No. 30106 along the strike. In hand-specimen the prominent banding of the unaltered gneiss is absent and the rock has an overall dull greasy-brown appearance, with a groundmass comprising 50 per cent of the rock. The pink microcline has entirely disappeared.

In thin section the influence of the dolerite is found to be profound. Quartz occurs as corroded residua rimmed, not by biotite as in No. 30102 but by the normal feldspathic matrix. The plagioclase has been thoroughly impregnated with potash feldspar and is now an antiperthite. The residua are strongly zoned, however, with a relatively

clear broad selvage of sodic plagioclase. Cordierite has undergone striking changes. In place of the colourless cordierite of No. 30106 this rock is characterized by a similar amount of a notably pleochroic variety (X = very pale yellow, Y = very pale lavender, Z = pale lavender ; $2V = (-)85$; dispersion very strong, $r < v$, thus suggesting a more ferriferous cordierite). The grain size, however, is about the same (1 mm.). Sillimanite has disappeared from the cordierite and pleochroic haloes surrounding zircons are not so prominent. Magnetite is plentiful and occurs as euhedra clustered around some of the original magnetite masses or as clusters from the decomposition of biotite.

The groundmass, which has an average grain size diameter of 0·2 mm., makes up to 50 per cent of the rock. It is composed predominantly of wedges of potash feldspar in exceedingly fine micrographic relations with quartz. Although the rock is perfectly fresh the resulting granophyre complex is stained a pale fawn colour. The potash feldspar (with 2V (− ve) about 85°) may be a non-twinned microcline. No albite was recognized, but a little sodic oligoclase is present as sub-rectangular crystals in the groundmass. Another mineral is a plentiful accessory in the groundmass. It occurs as non-pleochroic moderately refracting greenish-yellow tiny blades up to 0·1 mm. long. Owing to their minute size the optical properties are always confused with those of the host. Oblique terminations and two cleavages at (?) right angles in direction (?) // c suggest that the blades are monoclinic. The mineral almost invariably forms more or less radial growths where the groundmass of alkali feldspar has " corroded " original plagioclase. Since biotite has not been developed on metamorphism as it was in the hornfelsed adamellite No 30102 it is suggested that this mineral is its counterpart.

(*c*) *Hornfelsed Cordierite Gneiss* (No. 30108).—No. 30108 was collected 1 foot from the eastern edge of the dolerite dyke and is thus 2 feet from No. 30107 and 14 feet from No. 30106. The rock differs from No. 30107 in that metamorphism has been more severe. In hand-specimen the overall colour is a dark greasy brown and palimpsest gneissic banding can only be seen with difficulty. In thin section the texture is comparable. Quartz, which is sensibly uniaxial in Nos. 30107 and 30106, is strongly biaxial ($2V = (+)10°$). Cordierite may be slightly more pleochroic, and the unknown bladed greenish-yellow mineral is somewhat better developed, There is no sign of devitrified glass or mullite. Groundmass makes up nearly 70 per cent of the rock.

C. *Rheomorphic Vein Cutting Olivine Dolerite*

No. 30104 is representative of a remarkable dark grey vein which cuts the olivine dolerite, No. 30103. It is several yards long and about 1 inch thick, and has strike 230° and dip 45° N.W. It appears to

have originated within the highly-metamorphosed wall rocks to the west.

The vein consists of a fine-grained groundmass of plagioclase, strongly zoned from andesine to albite, and potash feldspar–quartz micropegmatite with abundant pale green sericite, numerous granules of dull black iron ore, wisps of graphite and irregular flakes of biotite (X = colourless, $Y = Z$ = khaki green). The average grain size of the groundmass is 0·04 mm.

There are no true phenocrysts, but xenocrysts and microxenoliths of all sizes are so abundant that it is difficult to decide the nature and origin of many mineral clusters in the groundmass. The most conspicuous foreign bodies are large very deeply embayed masses of quartz many of which are 3 or 4 mm. long. Several microxenoliths comprising large bundles of sillimanite needles occur (largest observed is 8 mm. × 2 mm.). A few strongly pinitized cordierite anhedra (some enclosing sillimanite needles) occur, and are in several places associated with irregular patches of dull black octahedra of magnetite (or some other ferriferous spinellid). Some irregular kaolinized xenocrysts of plagioclase occur. Occasional zircon and (?) monazite occur. Relict ophitic texture is readily seen in a " hydrated " xenolith of dolerite (2·5 mm. × 2 mm.). Pyroxene is psuedomorphed by yellowish-green serpentine which is studded with tiny octahedra of magnetite. Plagioclase is almost completely kaolinized and carbonated.

Unexpected mineral associations occur at the junction of vein and the host olivine dolerite. The clinopyroxene of the dolerite, where in direct contact with the vein, is always pseudomorphed by granular *hypersthene* instead of the customary biotite or amphibole. The hypersthene shows faint but characteristic pleochroism, straight extinction, and, with 2V (− ve) about 60°, has an approximate composition near Of 30 (mol. per cent).

D. *Assimilation of Granitic Material in Olivine Dolerite Magma*

About ¾ mile south of the location of No. 30103 the same dolerite dyke is shallow dipping (35° E.) and about 9 feet thick. In the field irregular granitic xenoliths may be seen in all stages of assimilation.

No. 30116 a typical specimen of " unadulterated " dolerite is indistinguishable in hand-specimen and thin section from No. 30103 No. 30119 occurs about 2 feet from No. 30116. In the field the dyke at this point shows a moderate amount of assimilation. In thin section several crystals of hypersthene occur (2V = (−)65°, straight extinction, weak pleochroism), and in places are found rimming augite. Olivine has been completely serpentinized. A complex of quartz-potash feldspar-oligoclase micropegmatite, and green diopside occurs as poikilitic patches partially pseudomorphing corroded xenocrysts of

feldspar, or as wedges in the groundmass. Calcite is a plentiful accessory throughout the rock. Amphibole is absent but semi-chloritized biotite wisps are not uncommon as partial replacements of pyroxene.

Petrogenesis

A. *Discussion of Chemical Analyses*

Chemical analyses of both fresh and metamorphosed micro-adamellite, and of the olivine dolerite which caused the metamorphism appear in Table I. This dolerite contains both modal olivine and non-xenocrystal quartz and a large amount (14 per cent) of " end phase " which consists of sodic plagioclase and accessory apatite, magnetite, chloritized biotite, calcite, and quartz. The chemical analysis and norm (Table II), however, confirm that the rock is an olivine dolerite. CO_2 is recorded as a notable minor constituent, but microscopic study suggests it may have been a little over-estimated. There is nothing in the analysis, however, which would lead one to expect much metasomatic action on the wall rocks.

Though the analyses of both fresh and altered micro-adamellite are similar, the writer considers that even small differences may have some petrogenetic significance. The unusual equality of the percentages for several constituents confirms field and microscopic evidence of the remarkable uniformity of the fresh micro-adamellitic dyke rock (e.g. MnO, K_2O, TiO_2).

In the final column of Table I are set out the approximate *percentage changes* apparently effected by the dolerite on the unaltered adamellite. Even allowing for possible minor errors in the analysis, and sampling errors, certain significant features do appear.

(1) *Actual* movement of material was small.

(2) *Percentage* movement seems to have been considerable.

(3) *Water* and some *soda* have been introduced into the hornfelsed rock.

(4) *Iron*, *lime*, and (possibly) *magnesia* have been removed from the hornfelsed rock.

(5) There has been 47 per cent *relative* decrease in Fe_2O_3 in the hornfelsed rock, but since FeO has increased (relatively) by 17 per cent this is taken to indicate that reducing solutions have converted much of the original ferric iron into " soluble " ferrous iron.

(6) Some of this iron seems to have been fixed in the ferrous state in the hornfelsed rock thus preventing complete removal by the hydrothermal solutions of the ferrous iron developed during the metamorphism.

The changes in normative composition of the two rocks are included in Table II, and in the final column the approximate percentage change of each constituent. Although actual change in the amounts of normative minerals is remarkably small, the changes are more obvious than from study of the chemical analyses themselves.

B. *Discussion of Petrographic Data*

Owing to the narrowness of the dyke and the diminution in grain size toward the edges the contact effects can scarcely be dominantly thermal. The phenomena here described probably occurred near the " blind top " of a dyke where temperature need not have been unduly high but where the water content of the magma was higher than elsewhere in the dyke. Truly thermal metamorphism is well described by Harrison (1908, pp. 36–7, 126–7, etc.), who shows that in granites metamorphosed in the vicinity of great dykes of dolerite, biotite, and hornblende are completely replaced by granular augite and magnetite dust. Nothing of this type has yet been seen in Central Australia.

Most metamorphic phenomena here described are common to all of the hornfelsed granitic rocks, but unless otherwise stated, actual features discussed below are taken from either the hornfelsed or fresh micro-adamellite. The following features are particularly noteworthy :

(*a*) Although *K_2O is constant* in both fresh and hornfelsed micro-adamellite, there has been a complete disintegration of potash feldspar and biotite. The liberated potash has attacked the plagioclase to form antiperthite. The rest of the potash has become fixed in the groundmass in intimate association with quartz to form micropegmatite or granophyre.

(*b*) Small tabular subhedra of plagioclase in the groundmass represent some of the plagioclase replaced during the formation of antiperthite, and also the *increase in normative albite* brought about by a slight introduction of Na_2O into the hornfelsed rock.

(*c*) Although *quartz* has been *strongly corroded* by the groundmass, the analyses show no significant change in SiO_2 content during metamorphism. Silica was required to fix as biotite the FeO formed by conversion of some of the Fe_2O_3 to FeO. It is therefore significant that thin sections always show " secondary " biotite rimming quartz as though it was an important factor in its corrosion. Complete disintegration of original microcline and biotite, development of antiperthite and introduction of a little Na_2O set free plentiful alkalies. Although normative quartz is substantially the same at the end of the metamorphic process, before " equilibrium " was set up there must have been considerable attack and reconstitution of original quartz by these substances, for molecules of alkali feldspar, anorthite, and biotite contain different proportions of SiO_2.

(*d*) In the more aluminous rocks (cordierite-sillimanite gneisses) *sillimanite has disappeared* during metamorphism from the cores of cordierite, and the *cordierite* has become *more ferriferous*. FeO, developed from Fe_2O_3 during metamorphism as in No. 30102, was probably "fixed" by sillimanite to produce a more ferriferous cordierite, thus :—

$$\underset{\text{Sillimanite}}{2Al_2SiO_5} + \underset{\text{Quartz}}{3\,SiO_2} + 2FeO = \underset{\text{"Cordierite"}}{Fe_2Al_4Si_5O_{18}}$$

If some such reaction occured it explains some of the corrosion of quartz and absence of secondary biotite. It will be recalled that in the micro-adamellites fixation of FeO has developed secondary biotite, and was thus a factor in the corrosion of quartz.

(*e*) *Zircon* and *apatite* are not broken down during this type of metamorphism.

(*f*) *Sphene* suffered slow recrystallization, but no titania was lost from the system.

(*g*) *Mobilization* of certain rocks was effected. Since the only rheomorphic vein was found to contain xenocrysts and microxenoliths of sillimanite and cordierite it is possible that the more aluminous metasediments were more amenable to mobilization than purely granitic rocks.

(*h*) *Metasomatic hypersthene* has been formed at the expense of augite where an alumina-rich rheomorphic vein was injected into the dolerite. As the author is unaware of any previous description of metasomatic hypersthene of this type, the remarkable phenomenon and its petrogenetic significance are discussed more fully in another paper (Wilson, 1952).

(*i*) The formation of *hypersthene in a basic magma* which has assimilated aluminous material is a well-known process (Read (1935) and Kuno (1950), etc.). In the southern extension of this dolerite dyke assimilation of granitic material has caused development of hypersthene in a dolerite which elsewhere is devoid of orthopyroxene.

ACKNOWLEDGMENTS

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DEPARTMENT OF GEOLOGY,
UNIVERSITY OF WESTERN AUSTRALIA,
NEDLANDS, WESTERN AUSTRALIA.

A Study of Granite Relief from South-West Africa

By J. A. MABBUTT

(PLATE II)

ABSTRACT

The writer describes the relief forms and destructional processes occurring in a group of granite hills in Damaraland, South-West Africa. The hills are attributed to the dissection of a former erosion surface by rejuvenated streams. Drainage incision has followed longitudinal and diagonal joint lines, which control the orientation and sub-division of individual groups of granite domes. The destruction of granite masses by plating, or the unloading of unweathered shells, produces the dome outline, whereas the development of vertical jointing leads to granite tors. Domes may be cleaved along transverse joints to form secondary domelets, or split longitudinally to form narrow whalebacks. The former are lowered by plating to flat dome forms; the latter are reduced by marginal fracturing, here termed mural weathering. Further wastage is by slow granular disintegration on low granite outcrops.

INTRODUCTION

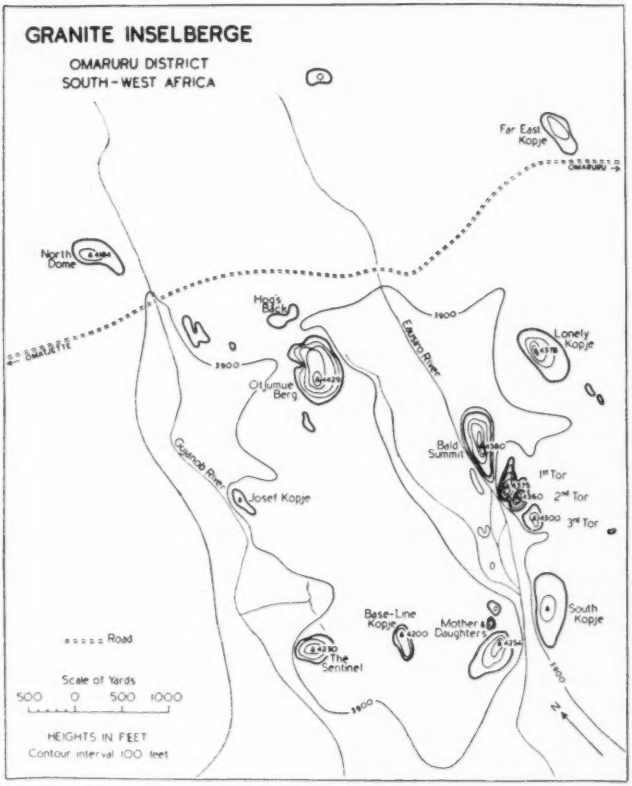
EXTENSIVE outcrops of the ancient crystalline basement have made Africa a favoured field for the study of relief development upon granite rocks. In Central and East Africa special circumstances, geologic and climatic, have produced the Bornhardt landscapes, the evolution of which formed the subject of a recent paper by King (1949). In December, 1949, the writer carried out fieldwork among granite hills on the Western Damaraland Plateau, 25 miles north-west of Omaruru, South-West Africa (Lat. 20° 10′ South, Long. 15° 40′ East). The relief forms and destructional processes were mapped during a systematic investigation of these features. The evidence bearing on Bornhardt landscape largely corroborates that given by Professor King's Rhodesian examples. In addition the landforms and processes are of interest as illustrating characteristics common to granite terrains in every continent and under a wide range of climates.

PHYSICAL SETTING

The granite hills mapped in Text-fig. 1 lie on the secondary divide between the Ugab and Omaruru rivers and are traversed by the Eausiro and Gujanob, which run south-south-west to join the Omaruru. These streams only flow after heavy rains, and otherwise appear as wide braiding channels filled with grit and sand. The area is also covered with a close network of minor, ephemeral stream channels.

The parent rock is the Salem granite, a grey porphyritic biotite granite accordantly intruded into schists and marbles of the Damara System during the final stages of a pre-Cambrian orogenesis. The sediments occur in thin belts striking north-east to south-west, sandwiched

between more extensive phacolithic granite bodies. No sediments outcrop in the area mapped. The granite is homogeneous save for occasional small schist inclusions, and thin aplite veins following primary jointing. In general it is morphologically unimportant, forming extensive level surfaces from which rise small groups of granite hills.



TEXT-FIG. 1.

The area falls in the zone of transition from the coastal desert to the interior steppe, and receives an average annual rainfall of 7 inches. The amount varies widely from year to year, and comes in the thunderstorms which approach from the east and north-east between November and March. Humidity is usually very low, as this region lies inland from the belt of coastal mists. Diurnal temperature ranges may exceed 60° F. in the month or two before the rains.

The hills under study rise from a level expanse of thorn-bush steppe,

broken by numerous rock outcrops, and diversified along the river-beds by zones of thicker vegetation with large trees.

The surrounding plateau forms part of the " African " surface, the product of sub-aerial erosion from Cretaceous times onwards, and characterized by its advanced state of planation and its inselberg landscape. The inselberge comprise true " Härtlinge "—ridges of Damara Marbles, resistant pegmatitic and aplitic granites, and younger Erongo intrusives—as well as the smaller exfoliation domes of Salem granite, which alone constitute Bornhardts in the sense used by King (1949). No general discussion of this inselberg landscape will be attempted here beyond the statement that it is in no way a relict feature, and that it is being actively shaped and extended under the present climate.

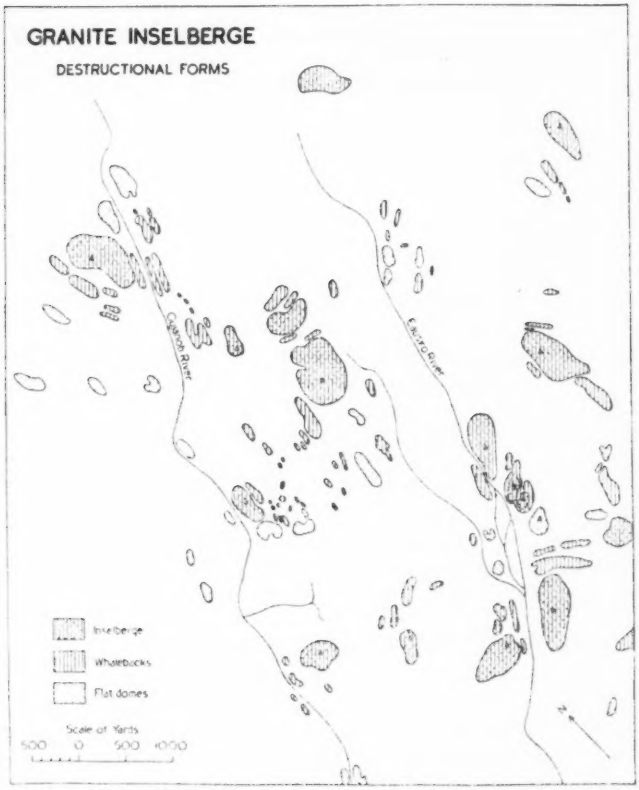
In this latitude the marginal flexuring consequent upon the uplift of the sub-continent has been less than in the regions north and south. The Great Escarpment is accordingly replaced by gentler transitional slopes from interior plateau to coastal plain. Nevertheless the Omaruru, in its incised lower course, clearly shows the effect of this recent uplift. In a smaller degree the Gujanob and Eausiro tributaries have shared this rejuvenation, and the granite domes mapped in Text-fig. 1 lie just within the area affected by the retrogressive erosional wave. Their summit plane at just over 4,100 feet above sea-level is continued north-eastwards in the undissected plateau surface. They therefore lend support to the view that " Bornhardts are only found where there are traces of two cycles of erosion " (King, 1949). The Bornhardt cycle is here in a youthful stage, but further downstream the same tributaries pass through a more evolved granite landscape in which little trace of the summit level survives.

The Effects of Structural Planes within the Granite

Primary structures within the granite have exercised negligible effect on the profiles of individual hills. The importance of primary jointing in controlling the layout of Bornhardt groups has, however, often been emphasized, and the pattern of relief in this area shows a similar control. Longitudinal joints followed by aplites trend 20° east of north, parallel to the regional strike of the intruded sediments and to the major axis of the phacolith. The river courses and lines of domes are similarly orientated, and this same trend is to be seen even more clearly in the map of destructional forms (Text-fig. 2). Diagonal joints running 65° east of north have controlled dissection within the groups, as shown by Bald Summit and the three adjacent Tors. In all these instances the joint system has entered into the plan of relief by way of the interwoven drainage pattern, by providing lines of weakness for the rock-removing agencies.

The profiles of the hills have been controlled by either, or both, of two types of division plane within the rock :—

(*a*) *Plate or sheet structures* formed by curvilinear division planes of wide radius, accordant with exposed rock surfaces. These are secondary



TEXT-FIG. 2.

features which may intersect primary structures at marked angles. In New England quarry sections such planes have been seen developed 150 feet or more beneath the surface (Jahns, 1943). In depth the sheets are thicker, flatter, and more persistent, but near the surface they break into lens-shaped plates ranging from a few inches to one or more feet in thickness. They may overlap or be bounded by joint planes. Their depth of occurrence, thickness, and freshness preclude the

possibility of formation by exterior weathering agencies, and their accordance with exposed surfaces supports the concept of dilatation, or fracture due to unloading (Gilbert, 1904). The process is a slow one. In the Yosemite Valley, Matthes (1930) has noted the negligible achievements in post-glacial time. It is opposed to, and inhibited by selective corrasion, which in extreme cases can cause complete re-orientation of the planes of fracture, but only during active denudation can it attain its fullest expression.

(*b*) *Sub-rectangular jointing*, whereby the granite is split into cuboid blocks, may oppose or modify the development of plates. Extremely close jointing accounts for those examples from which plate structures are absent, but in the area studied jointing had served to modify rather than to obliterate such structures.

Plate structure is directly reflected in the smooth outlines of bare granite domes, while the break-up of the rock by jointing produces the surfaces of piled blocks which will be distinguished as tors. These two forms respond in different ways to the denuding agencies. Their parallel modes of destruction and the resultant products will be discussed below.

Granite Domes and Associated Features

The reduction of domes takes place by the shedding of successive rock plates. Much of the controversy on this subject has arisen through a confusion of terms. Plate removal should be distinguished from the separation of thin weathering scales or shells from exposed rock surfaces, a process by no means restricted to plutonic rocks. Both processes have, however, been termed exfoliation. Exfoliation weathering is the result of expansion of a weathered crust due to chemical change, probably motivated by surface heating in the presence of moisture. Laboratory tests suggest that the physical strains set up by insolation alone are inadequate to cause the disruption of fresh rock in this manner.

The generic term exfoliation must therefore be understood to comprise two specific processes, for which the terms *plating* and *scaling* are suggested.

Most of the larger domes exhibit several differently centred plating systems, and their surfaces may consist of numerous convexities often separated by joint planes. In such cases the intervening concavity is accentuated as plating proceeds, while the growth of the cleft may be speeded by weathering and surface channelling, since rainwater, rock debris, and vegetation become concentrated within the hollows. In this manner a dome may be split or trimmed along a joint plane, and some of the domes, such as Bald Summit, show this orientation most markedly. Otherwise the smooth homogeneous front renders

the dome an extremely stable form, as shown by the fact that true exfoliation domes formed the largest surviving features in the area studied.

The process of plate removal is a gradual one. In the initial stages the plate remains in position, and only a hollow sound as one walks over the granite surface may indicate that it has sprung away from the rock beneath. Within the loosened carapace of a symmetrical dome, radial and circumferential fractures develop. On dome summits and slopes less than 20°, or where supported at the dome foot or by irregularities in the dome surface, the segments break down in situ. Here they form blocks or scales, depending on the thickness of the original plate. Elsewhere the segments break away and slide down to feed the talus around the dome margin and in the surface concavities described above. In this way smooth steep-sided domes remain comparatively free from surface debris.

The cleavage of domes along joint planes produces two distinct sets of features :—

(*a*) Erosion following longitudinal joints eventually isolates the long smooth ridges here referred to as *whalebacks*. These occur adjacent to the flanks of major domes, and are characterized by steep sides and narrow flat crests. While the crest is slowly lowered by plating, fracturing is common along the steep margins, opening up vertical fissures parallel to the axis of the whaleback. This is illustrative of a general rule that abrupt shoulders constitute a favoured point for the inception of jointing on an exfoliating surface. Repetition of the process causes lateral shrinkage of the whaleback within parallel strips of granite, which subsequently break up into joint blocks and come to resemble lines of masonry. Destruction by marginal fracturing has been named *mural weathering*. It is especially important in the reduction of whalebacks, and results in the increasing dominance of the longitudinal joint direction in the latter stages of granite relief development.

The longitudinal fissures opened up by mural weathering may be widened by stream attack, while the individual joint blocks within the ridges are rounded off and reduced in size. Where the blocks are in close contact, deep spheroidal weathering is the rule, leading to the crumbling of the whole block in situ : if the block is isolated, so that the weathered scales can fall free, spectacular mushroom rocks may develop.

(*b*) Erosion along transverse joints may split the dome into equal parts or at least separate off granite masses more nearly circular in plan than whalebacks. First, Second, and Third Tors are examples of the former case, and the Hog's Back of the latter. Findings in this area endorse Gilbert's (1904) statement that the separated portions evolve quite independently and that exfoliation patterns seen in the one will

not be continued across into the other. This is shown by the opposing walls of the gap between First and Second Tor where each side is convex towards the other (Plate II, fig. 1).

Although mural weathering does occasionally operate along the margins of many such domelets, the shoulders are generally less abrupt than on whalebacks, and where granite surfaces slope gently to the surrounding plain they are proof against marginal fracturing. The domelets are eventually lowered by plating to form broad flat domes which may rise only a few feet above the level of stream planation.

The distribution of flat domes is shown in Text-fig. 2. They occur peripherally to the large inselberge and whalebacks, as might be expected of more evolved features. Those occurring on the lateral margins are conceivably the remnants of whalebacks lowered to stable forms. Larger ones occur in prolongation of major domes, separated from them by wide transverse gaps, and have probably evolved from secondary detached domelets in the manner just described. If one accepts the view of Mennell (1904) that domes coincide with zones of sparser jointing, broad flat domes rather than narrow whalebacks are to be expected within those same zones.

Further lowering of the granite surfaces takes place by slow granular disintegration as a result of chemical weathering. Eventually, the flat domes are reduced to gentle granite swells, often completely veneered with fragments of the weathered rock, and separated by shallow stream channels.

The smooth surface of a granite dome offers little foothold to selective weathering processes. Under the prevailing climate, surface weathering in this area is slow. It takes the form of granular disintegration, uniformly attacking the whole of the dome face. The loosened material is removed, and the slopes kept smooth by rainwash. Only where unequal resistance is met with does this process become apparent, as where schist inclusions, 4 to 5 inches across, had weathered out, and protected tiny granite pedestals up to a foot high. Such irregularities of the surface tend to channel run-off, and the initial unevenness is increased.

Along aplite veins, or other lines of weakness, solution channels develop. Similar features are formed as outflows from plating concavities which act as traps for surface water. Solution is aided by organic acids, since such clefts are favoured spots for plant growth on otherwise bare dome surfaces.

Both these exceptions show the importance of the homogeneity of the granite as controlling its normal erosion forms. They also exemplify corrosive and, to a lesser extent, corrasive processes which have often been overlooked in accounts of granite relief.

On homogeneous domes, thin circular scales of deeply weathered

granite up to a few feet in diameter may be detached. This is the equivalent of spheroidal weathering on granite blocks. The shallow scars are rapidly obliterated on steep slopes, but on level surfaces they may trap rain-water and be deepened and widened by solution into shallow weather pits. On Bald Summit such pits were as much as 6 inches deep and 5 feet across. They generally had no outlet and were floored with loose felspar phenocrysts. More evolved forms, developed under a more humid climate, have been described from the Southern Piedmont granites (Smith, 1941).

Granite Tors

Tor and dome faces are often found to alternate on the same relief feature. In such cases the dome outlines are commonly continued in the faces of little-eroded tor structures. Even where the whole summit has been fractured plate structures are usually apparent within the mass, and frequently control the form and arrangement of joint blocks. There is no evidence that the granite is not homogeneous throughout the area, and such close jointing seems to be a modification of the usual plate structures arising under the following conditions :—

(*a*) Where plate partings are widely spaced the thicker plates are more liable to be broken by vertical joints into granite columns and blocks. This explains the frequent cases where a tor summit is found resting on a broad dome, the tor representing the unconsumed portion of a thick plate which has undergone fracturing by jointing. In such cases the upper and basal surfaces of the tor structure are distinctly curvilinear. Confirmation is provided by examples where jointing has only affected portions of successive thick plates and the relationship of tor and dome surfaces is left quite clear. It was impossible to decide whether the onset of jointing had been favoured by under-developed plate-structures, or whether the initiation of jointing at an unusually early stage had prevented the sheets from sub-dividing into the thinner plates more commonly met with in the area.

(*b*) An examination of the cases where tors and domes alternate on the same feature shows that tors frequently coincide with the steeper faces. Granite plates of appreciable thickness are very liable to break into joint blocks on abrupt shoulders. If the original plate stood very steeply and was adequately supported from below the joint blocks are formed in a stable position, and weather down in situ.

(*c*) Between the numerous convexities making up the surface of a single dome, plates may develop with concave lower surfaces. They are usually of above average thickness. Their form and position are such that the joint blocks produced by their break-up remain in place, forming minor tor faces. These must be distinguished from the scree fillings of surface concavities.

Every gradation exists between tors and granite scree. In the former the contacts between blocks are joint planes and the blocks themselves are cuboid in shape, while scree consists of every size and shape of fragment. The angle of repose of granite scree rarely exceeds 35°, whereas tor faces range from horizontal to vertical. Tor faces generally continue the convex outlines of adjacent dome structures, while scree surfaces are true gravity slopes. Most tor faces and, to a much lesser degree, dome surfaces are fringed by scree.

Individual joint blocks within tor faces are attacked by spheroidal weathering, which may be grouped with scaling as a chemical or physico-chemical process. The granite scree below tors is mainly a product of this form of break-down, and its relatively greater abundance there shows how much speedier are the degradational processes on joint blocks than on smooth dome surfaces.

The Granite Dome Cycle

Rejuvenation in a granite area of small relief leads to stream incision, the pattern of which is normally controlled by the longitudinal joint system. As the relief increases, lines of granite domes are excavated, presumably along zones of sparser jointing. The gaps separating the domes in any one line generally accord with the trend of transverse or diagonal joints.

The domes may subsequently be cleaved by solution channelling along these master joint directions. Longitudinal cleaving produces whalebacks, which evolve by mural weathering into lines of boulders and narrow flat domes. Splitting along transverse lines produces secondary domes which are lowered by plating to flat dome forms. By scaling and spheroidal weathering, the products of plating and jointing are broken down to transportable dimensions, and by slow granular disintegration the flat dome forms are lowered to level rock surfaces. It seems justifiable to regard the tor as a variant introduced by special conditions into the foregoing cycle.

Conclusion

The similarity of relief exhibited by granitic rocks under widely differing climates and processes emphasizes the common factor—a massive, homogeneous, fairly resistant rock-type. The variables fall into three groups. The first includes those structural features which control the patterns and modify the outlines of the erosional forms. The second group can be summed up under the term " available relief ". Active relief formation is necessary for the full development of processes whose base-level is the level of the adjoining plain. The third comprises climate and weathering. The rapid chemical weathering of the humid tropics can alone obliterate the familiar outlines of granite relief. The

area chosen for study is favoured by the homogeneity of rock structure, the recency and uniformity of epeirogenesis, and a semi-arid climate under which the resultant landforms are but slowly modified by weathering. Further studies are needed, in other continents and under other climates, in order to establish a general scheme of granite relief evolution.

ACKNOWLEDGMENTS

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DEPT. OF GEOGRAPHY,
UNIVERSITY OF CAPE TOWN,
SOUTH AFRICA.

EXPLANATION OF PLATE II

FIG. 1.—Radial and circumferential fractures on a detached plate on First Tor. The opposing convexities of First and Second Tors may be observed.

FIG. 2.—Jointing developed on unusually thick plates, showing the relationship of tor and dome structures.

FIG. 1.

FIG. 2.

GRANITE RELIEF, S.W. AFRICA.

Metamorphic Differentiation of Talc-Magnesite-Chlorite Rocks in Shetland

By M. S. Amin

Abstract

Practically monomineralic masses of talc, of magnesite, and of chlorite are formed in talc-magnesite-chlorite-rocks as a result of localized shearing and associated hydrothermal activity within deformation-belts.

1. Introduction

DURING a recent study of the serpentine bodies of Unst, in the Shetland Islands, the writer observed several excellent examples of the production of practically monomineralic masses of talc, of magnesite, and of chlorite in the shear-zones traversing rocks made of their mixed components. Such a purification process controls the economic working of the talc deposits of Unst and of those formerly worked in the adjacent island of Fetlar. It is the purpose of this communication to give an account of the occurrence of the mixed talc-magnesite-chlorite-bodies and their modification into their pure components. Most attention will naturally be paid to the Unst examples.

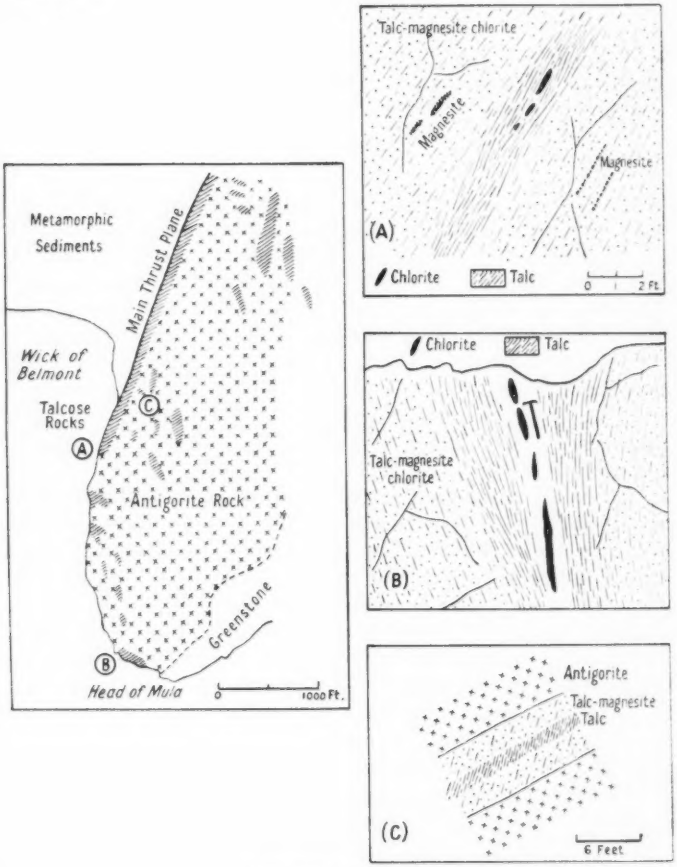
The geology of the Unst serpentine bodies has been dealt with in recent times by F. Coles Phillips (1927) and by H. H. Read (1934). The latter has shown that the talc-magnesite-chlorite-rocks,[1] associated with antigorite-rock, have been produced along the thrust-zones that form the base of the serpentine masses and also along certain movement-planes within the serpentines (Read, 1934, pp. 662–4, fig. 7). The present writer is of the opinion that the tectonic deformation was accompanied by the passage of hydrothermal fluids along the movement-planes which was responsible for the transformation of the serpentines into the rocks here studied. As already noted, localized shearing within the deformation-belts and associated hydrothermal activity permits the segregation of the individual components in the mixed deformation-products affected. A selection of the examples of this purification is now described and the process is then discussed. The localities dealt with in particular are Belmont, Queyhouse, and Clibberswick in Unst, and Hesta Ness in Fetlar.

2. Unst Examples

(*a*) *Belmont.*—At Belmont, in the south-western corner of Unst, antigorite-rock and talc-magnesite-chlorite-rock are well developed

[1] These rocks contain only a little chlorite but this designation is used to emphasize their relation to the segregation of chlorite as well as of talc and magnesite.

adjacent to the main thrust-plane along which the Main Serpentine has been thrust westwards over the metamorphic rocks, as shown in Text-fig. 1.

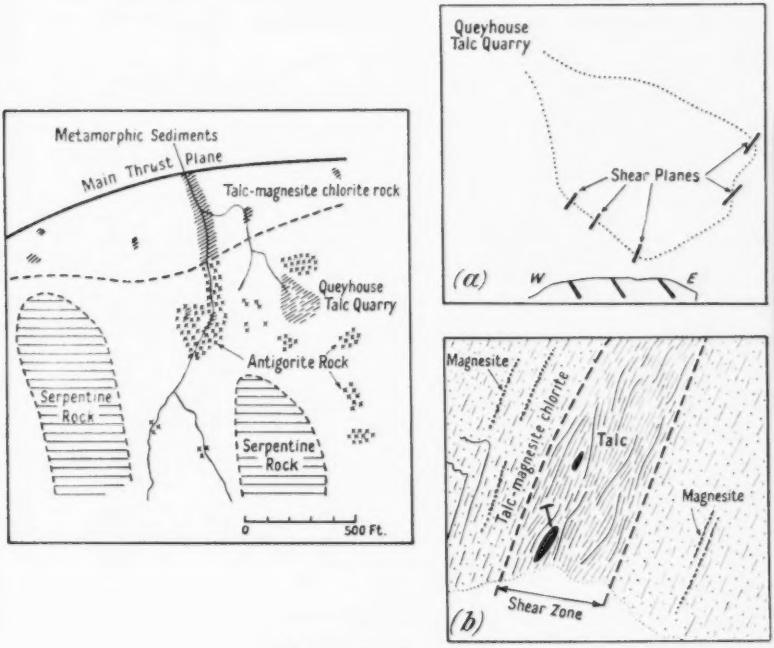


TEXT-FIG. 1.—Belmont.

The thrust-plane is lined with talc-magnesite-chlorite-rock, which also forms lenticular masses within the antigorite-rock. At Wick of Belmont, near the thrust-plane, the talc-magnesite-rock is traversed by a minor shear-plane which is marked by the development of a zone of contorted talc-schist up to 2 feet in thickness. The talc-schist encloses lenticular masses, up to 1 foot in length, of massive chlorite-rock which have rather sharp contacts. Along either side of the

talc-schist, there is seen a gradual passage into a poorly schistose talc-magnesite-chlorite-rock which has streaks, veinlets, and lenticular nodules of magnesite reaching a foot or so in length (Text-fig. 1, A).

At Head of Mula, a talc-magnesite-chlorite-body is traversed by a shear-plane marked by chlorite-rock and talc-schist which merges into the talc-magnesite-chlorite-rock on either side (Text-fig. 1, B).

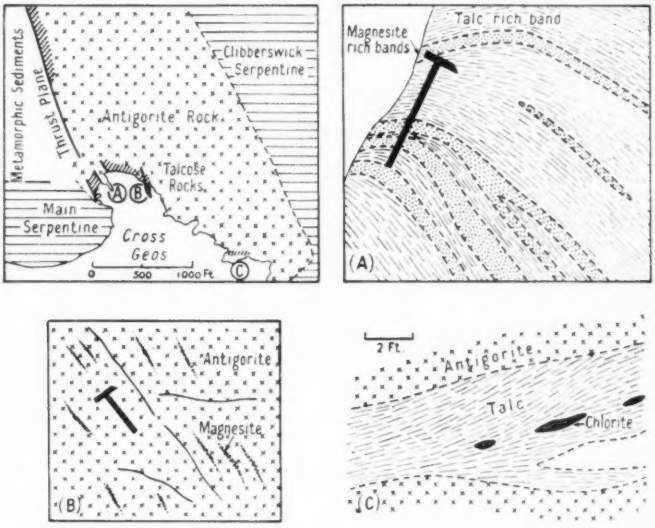


TEXT-FIG. 2.—Queyhouse.

Incomplete examples of segregation are numerous at Belmont. For example, a talc-magnesite lenticle 8 feet in width and 30 feet long is enclosed in antigorite-rock (Text-fig. 1, C); its centre is made of talc-schist about 2 feet in width, followed on either side by a "gritty" magnesite-rock with a little talc which has a rather sharp contact against the antigorite-rock. At the contact the antigorite-rock contains magnesite but this material soon fades into the normal country-rock away from the contact.

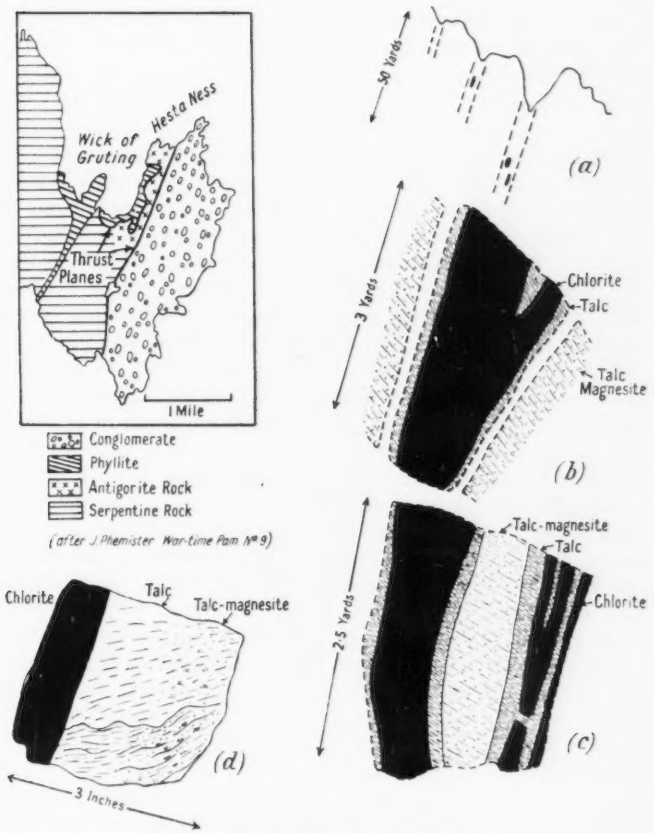
(*b*) *Queyhouse.*—Metamorphic differentiation of these rocks is well displayed at Queyhouse at the north of the Main Serpentine where the

talc-magnesite- and talc-schist are extensively quarried. The country-rock of the area is antigorite-rock adjacent to the main basal thrust-plane (Text-fig. 2). The antigorite-rock encloses lenticular or irregular bodies of talc-magnesite-rock in one of which the talc quarry is operating. The body (Text-fig. 2, a) is about 300 feet in length. The quarry was first opened in a poorly schistose talc-magnesite-rock but was later extended southward where the rock is traversed by shear-planes striking 25°–35° and dipping south-east. These planes are



TEXT-FIG. 3.—Clibberswick.

marked by the presence of contorted talc-schist of striking purity which gives a fine quality of flaky talc (Text-fig. 2, b). The talc-schist is associated with lenticular masses of almost pure massive chlorite-rock (solid black in Text-fig. 2, b), the length of the chlorite lenses ranging from a few inches up to 4 feet and their width reaching a foot. Both the talc-schist and the chlorite-rock develop coarse flakes of transparent varieties. The talc-schist merges outward on either side into the talc-magnesite-rock with the appearance and concentration of magnesite ; in this passage zone the magnesite is occasionally concentrated into streaks or narrow lenticles running parallel to the shear-planes and having a similar dip and strike. In developing the quarry attention is directed to the presence of the chlorite-rock as an indication of pure talc-schist.



TEXT-FIG. 4.—Hesta Ness (Fetlar).

(*c*) *Clibberswick*.—At Clibberswick, in the north-eastern part of Unst, the thrust on which the Clibberswick Serpentine is moved over the Main Serpentine is excellently exposed (Text-fig. 3). At Cross Geos, where the actual thrust-plane is seen in the cliffs, antigorite-rock forms kernels in the talc-magnesite-rock, both rocks enclosing streaks or elongated lenticles of magnesite which strike and dip parallel to the thrust-plane (Text-fig. 3, B). The talc-magnesite-rock also develops a banded structure marked by alternating magnesite-rich and talc-rich bands which vary in thickness from 1 to 4 inches ; they dip and strike with the thrust-plane (Text-fig. 3, A).

At a locality ¼ mile east of Cross Geos the antigorite-rock encloses

a small belt of talc-schist which strikes 80° and is almost vertical. The talc-schist contains small lenses up to 2 feet in length of massive chlorite-rock (Text-fig. 3, C).

3. Fetlar Example

At Hesta Ness, in the north-east of Fetlar, talc was at one time extensively worked. The country-rock of the occurrence is a talc-magnesite-rock associated with antigorite-rock formed along the thrust-planes separating the phyllite and conglomerates from the serpentine mass in the east side of the Wick of Gruting (Text-fig. 4). The talc-magnesite-rock has a schistosity striking 125° and dipping to the north-east at 30°. On the cliff of Hesta Ness, talc was quarried along narrow gullies and trenches opened in the talc-magnesite-rock (Text-fig. 4, a). Along these openings numerous narrow relics of chlorite-rock are formed extensively, ranging from 1 to 15 feet in length and up to 8 feet in width. They are usually enveloped in a sheath of talc-schist which separates them from the talc-magnesite-rock (Text-fig. 4, b, c). Both the chlorite-rock and the talc-rock are schistose in conformity with the talc-magnesite-rock. The attitude of the talc-chlorite associations, which is oblique to the regional schistosity, presumably controlled by the flat thrust-plane as mapped by J. Phemister (1941), is nevertheless parallel to the main thrust-plane on the eastern side of Fetlar.

The contact of the chlorite-schist and the talc-schist is fairly sharp when compared with the gradational contact between the latter and the talc-magnesite-schist.

4. Petrography of the Differentiated Rocks

The talc-magnesite-chlorite-rock is composed of talc, magnesite, chlorite, decomposed chromite, and sometimes magnetite. The talc forms fine or medium-sized flakes mixed with medium magnesite grains. The carbonate has $\grave{\epsilon} = 1{\cdot}610$ and $\omega = 1{\cdot}705$ and often occurs in clusters as at Queyhouse or may be in very small grains or fine dust-like particles. These two components make the general matrix of the rock but in this there occasionally occur larger flakes of talc and veinlets or irregular patches of magnesite. Chromite grains are few and scattered ; they are almost opaque and are fringed with magnetite granules or dust. In a few cases chromite grains retain relics of chlorite flakes around them. The rock is generally massive except when it approaches the shear-planes ; at Hesta Ness it is schistose.

The talc-schist is usually schistose and contorted. Its colour is pale green and it sometimes shows a pearly lustre, as in Queyhouse. The purest variety of this locality is entirely talc except for a very few

grains of iron oxide. Occasionally the rock shows scattered magnetite grains or is stained with decomposed iron oxides.

The chlorite-rock is an olive green rock, usually massive, except at Hesta Ness where it is schistose. It is made of fine to medium-sized flakes of chlorite but at Hesta Ness and at Queyhouse very large flakes are formed. The chlorite is pleochroic with X yellowish-green, Y blue, Z blue ; the flakes give yellowish-grey interference colours, possess a negative sign of elongation, and have a mean refractive index of 1·587–1·590. Large flakes from Queyhouse gave a positive optic sign with $2V = 32°$.

The magnesite rock is usually massive and rather coarse grained. It gives $\grave{\epsilon} = 1{\cdot}608$, $\omega = 1{\cdot}697$ to $\grave{\epsilon} = 1{\cdot}620$, $\omega = 1{\cdot}720$. Undulose extinction and distorted lamellar twinning are shown by a coarse " pegmatoid " variety from Belmont.

5. Discussion

The evidence detailed permits of certain generalizations concerning these Shetland occurrences. The talc-schist occupies certain shear-planes traversing talc-magnesite-chlorite rock ; the chlorite-rock is always enclosed in talc-schist ; the magnesite-rock, on the other hand, occurs in the talc-magnesite-chlorite-rock and not in the talc-schist. The differentiated concentrates are localized on the shear-planes and are aligned parallel to them. The talc-schist is usually contorted and dragfolded. The chlorite-rock and the magnesite-rock are, however, almost massive (except at Hesta Ness), suggesting that, although their initiation and localization were controlled by the shearing, their actual formation was slightly later. The schistosity at Hesta Ness is likely to be due to the more prolonged shearing undergone by Fetlar rocks in general.

The formation of almost pure rocks composed of talc, of chlorite, or of magnesite in association with talc-magnesite and serpentine rocks has been described by a number of previous workers. Thus, Wilcockson and Tyler (1933, p. 313) recorded quartz-carbonate-rocks from the cores of talc-carbonate-bodies in the Sudan. An example of carbonate concentration as magnesite-marbles in the talc-carbonate-rocks of Que Que, in Southern Rhodeisa, was described by A. M. Macgregor (1932). Talc and chlorite rocks have been noted at the margins of the famous Vermont talc deposits by Gilson (1927) and Hess and Phillips (1936), and similar phenomena were described by Cooke (1937) from the soapstone deposits of Quebec. In these American occurrences the lenticular bodies of serpentine or talc-carbonate rocks have a margin of talc-rock against chlorite-schist which abuts against siliceous country-rock. These marginal chlorite and talc rocks were attributed by Hess and Phillips to metamorphic differentiation at the contact of

two contrasted rock-types. A similar relation was described by F. Coles Phillips (1927, p. 641) from Oddsta, on the western shores of Fetlar.

In all the occurrences described, the carbonate seems to become concentrated in the interior of the talc-carbonate-masses away from the field of reaction and talcose and chloritic rocks to be formed at the margins between serpentine and country-rocks. This latter position is different from that of the concentrations described in the present paper. The only description of talc and chlorite rocks similar in position to those of Shetland is given by Hess (1933, p. 407) ; chlorite and talc veins in the Virginia Soapstones are related by him to interior replacements along paths of migration of hydrothermal fluids.

For the Unst and Fetlar occurrences the present writer considers that the formation of talc, chlorite, and magnesite rocks is the result of metamorphic differentiation of sheared talc-magnesite-chlorite-rocks. Shearing permitted the hydrothermal fluids to circulate freely along definite planes. The most soluble constituent, the magnesite, is removed from the shear-zones and redeposited in the parent rock in planes parallel to those of the shears. The shear-zones are therefore enriched in the relatively insoluble constituents, talc and chlorite. Since the chlorite is not abundant in the parent rock it is represented only by small lenses in the talc-rocks.

The sorting-out of metamorphic minerals is an operation of metamorphic differentiaton, as defined and described by Stillwell (1918), Eskola (1932), Read (1933), Chapman (1950), and others. Stillwell emphasized solid diffusion as the mechanism of differentiation, Read preferred the action of solvents. In the Shetland examples the rocks were presumably soaked in hydrothermal fluids so that solid diffusion is ruled out.

The cases of metamorphic differentiation described from the Shetlands illustrate the classification of the processes involved as elaborated by Eskola. The removal of magnesite represents Eskola's solution principle, while the concentration of talc and chlorite in the shear-belts represents the principle of enrichment of the stablest component. The whole process of metamorphic differentiation in the Shetland examples was initiated, controlled, and localized by shearing, in that paths were opened for circulating fluids.

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DEPARTMENT OF GEOLOGY,
IMPERIAL COLLEGE,
LONDON, S.W. 7.

The Age Relationship of the Granophyre and Basalt of Orval, Isle of Rhum

By George P. Black

Abstract

On Orval, in the Isle of Rhum, Tertiary plateau lavas directly overlie the granophyre of the ring-complex. Judd considered that the Orval basalts rest unconformably upon an old land surface cut in the granophyre ; but on the supposed existence of veining and metamorphism later workers, in particular Geikie and Harker, concluded that the granophyre had intruded the volcanic pile. The author's re-examination of the Orval rocks supports Judd's early interpretation.

Introduction

ORVAL is a peak in the west of Rhum. Near the summit an outlier of Tertiary olivine-basalt lavas rests on the granophyre which forms the underlying and major part of the hill. The lavas cover a quadrilateral area of approximately one-sixth of a square mile. The present upper surface is roughly horizontal, but the lower surface dips in a direction east of north. As a result the lavas vary in thickness from 500 feet on the north and east sides of the quadrilateral to zero on the south and west sides. The northern and eastern boundaries are marked by cliffs some 200 feet high, which reproduce in miniature the scenic features of the well-known Storr ridge in north-east Skye.

Neighbouring hills, to which reference will be made later, include Fionn-Chra, with Tertiary basalt lavas resting on Torridonian Sandstone, the basalts themselves being covered by flows of mugearite ; and Bloodstone Hill, where mugearites directly overlie the Torridonian Sandstone with no intervening basalts (Text-fig. 1).

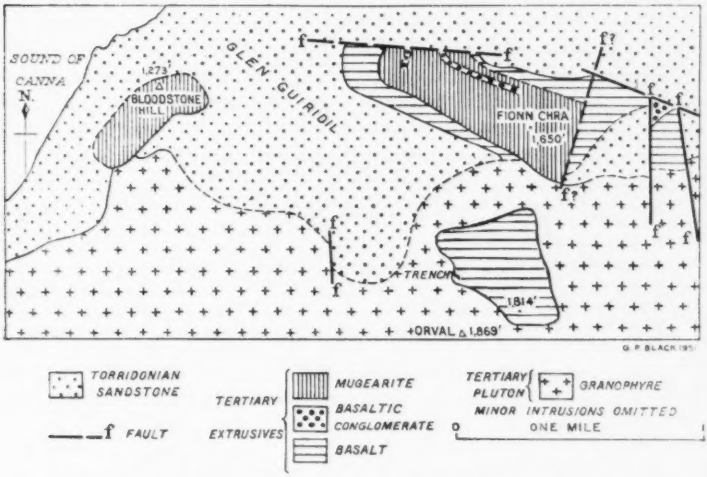
The granophyre of Orval is an integral part of the Tertiary plutonic complex of Rhum, while the basalts are part of the Tertiary lava plateau of the same island. A study of the relations of the basalts and granophyre of Orval may therefore help to establish the time-sequence of igneous activity in Rhum.

Previous Work on the Orval Area

Judd (1874, p. 254) expressed the view that the basalt lavas rest unconformably on the granophyre. He adduced no supporting evidence, possibly because he believed his view to be self-evident.

On the other hand, Geikie (1897, vol. ii, p. 404) stated that an outlier of lavas " lies upon the porphyry (i.e. granophyre) of Orval as a cake that dips gently northward. . . . It has undergone contact-metamorphism and tongues from the underlying rock project up into it ". From this it is clear that he believed the granophyre to be younger than the overlying lavas.

Harker (1908, p. 60) supported Geikie's view. " In two localities the basaltic lavas assume a somewhat different aspect in the field, being metamorphosed in proximity to plutonic intrusions . . . One of the localities alluded to is the north-eastern shoulder of Orval, in Rhum, where a patch of basalt half a mile long rests on, and is surrounded by, granite which has produced in it a noteworthy degree of metamorphism."



TEXT-FIG. 1.—Map of the geology of the neighbourhood of Orval.

More recently Bailey (1944, p. 184) holds the view that the metamorphism is only slight, while Tomkeieff (1942, p. 3) states that " The lavas near the granophyre are altered and the granophyre, in its turn, assumes a fine-grained texture near the contact with the lavas ".

On the whole, therefore, Geikie's view is at present generally accepted.

RE-EXAMINATION OF PREVIOUS EVIDENCE

Since 1949 the present writer has been engaged in investigating the southern and western areas of the Isle of Rhum. A thorough examination of the exposures around Orval has been included in this research.

(*a*) *Geikie's " Tongue of Granophyre "*

At the base of the lava cliffs blocks were found consisting of melanocratic rock traversed by a network of leucocratic veins. It is possible that Geikie assumed that these had fallen from the lava cliffs above.

In fact, detailed examination has shown that these blocks are glacial erratics of peridotite. The veins are the felspathic veins characteristic of much of that rock in Rhum. The basal lava even though coarsely jointed, shows no signs of " tongues from the underlying granophyre ".

(*b*) *Metamorphism of the Basalts*

Bailey (1944, p. 184) states : " The granophyre has altered the lavas so little that of the several slices which I have examined only the one mentioned above (S. 2711) showed indubitable contact-alteration."

Through the courtesy of H.M. Geological Survey the present writer was permitted to examine this one slice (S. 2711) in which Bailey found metamorphism. The locality of the slice is given as " north-east flank of Orval, Rum ". The rock shows incipient granulitization of the pyroxene, and is undoubtedly slightly contact-metamorphosed.

The absence of metamorphism, however, from the other slices examined by Bailey is very significant. To this the present writer would add that none of the slices he has prepared shows any trace of contact-metamorphism. The basal margin of the lowest basalt is found in thin-section, to be a normal variolite with no signs of metamorphism. The rock consists of numerous rods of felspar, slightly chloritized, small grains of a brownish augite, mostly quite fresh, and small granules of iron ore, all set in a brownish glassy groundmass. No biotite is present either as a primary or secondary occurrence, but unaltered serpentinous material occurs throughout the rock.

Since the plutonic granophyre must be either older or younger than the basalt lavas, and since the available evidence is almost wholly in favour of the former alternative, the exceptional occurrence of slight metamorphism in the lavas, as found in S. 2711, would appear to be purely local and due to some agency other than the granophyre. It may have been caused by some minor igneous body such as a dyke. Unfortunately the locality of the slice was not sufficiently clearly defined to make further investigation possible.

Further Evidence

In the course of the present investigation much new evidence bearing on the problem under discussion has been obtained.

(*a*) The thickness of the basalt pile throughout the region was investigated. On Orval the basalts show a maximum residual thickness of 500 feet, despite an upper surface determined by erosion. On Fionn-Chra the basalts, resting on Torridonian Sandstone and covered by mugearite, are 150 feet thick. At Bloodstone Hill, where mugearites lie directly on Torridonian Sandstone, basalt is lacking. Explanation of this rapid variation of thickness would not be rendered easier by

accepting Geikie's view that the lava pile on Orval has been invaded and presumably partially destroyed by the underlying granophyre.

(*b*) The variety of rocks with which the granophyre is in contact suggested an inquiry into the occurrence of xenoliths. Wherever the granophyre is in contact with a basic rock of undoubted greater age, it has been found to be crowded with basic fragments of all sizes for many feet from the contact. Examples of this occur where the granophyre is in contact with gabbro (Harker, 1908, p. 105), and with the peridotite (ibid., p. 105). Along the contact of the basalts and granophyre on Orval, however, the present writer found the granophyre to be free from xenoliths. Moreover, it has a content of ferromagnesian material no greater than that normally found in parts of the mass furthest removed from all contacts. This absence of xenoliths and of reaction products is inconsistent with Geikie's hypothesis.

(*c*) Specimens, equally exposed to present-day weathering were taken from the granophyre in proximity to its contact with the basalt ; and these were examined microscopically with a view to determining the presence or absence of a fine-grained chilled margin. The granophyre 5 feet below the lavas is of a normal coarse type with a grain-size of approximately 1·5 mm. The orthoclase of the rock is extensively clouded, generally brownish, and in parts almost opaque. The soda-plagioclase, however, is much less decomposed. The whole rock is stained in places with limonitic material. Specimens taken from nearer the margin have the same grain-size of about 1·5 mm. The orthoclase, however, is more turbid, the turbidity is seen to be affecting the plagioclase, and the limonitic staining is more pronounced. There is therefore no sign of a fine-grained margin such as would be expected in an igneous contact. The upward increase of the turbidity in the felspar and of the limonitic staining suggests that part of this decomposition had been achieved in pre-basaltic times. The evidence is again consistent with the view that the contact plane is an erosion surface.

(*d*) A microscopic examination was also made of specimens collected from the lower margin of the lava flow in contact with the granophyre. These specimens contain small crystals of quartz and the question at once arises whether they are xenocrysts or not. If this quartz had crystallized from the basalt it should be interstitial. The quartz crystals which actually occur, however, are rounded in shape ; they often have a strained extinction ; and the basalt does not appear to have reacted with them to any appreciable extent. Moreover, similar quartz crystals, again with a strained extinction, occur in the near-by granophyre and Torridonian Sandstone. The quartz crystals in the basalt, therefore, must be considered as xenocrysts. The presence of this xenocrystal quartz in the basal basalt indicates that this flow may have

traversed an arenaceous or granite surface. If this be so, the present basal flow must be part at least of the original basal flow. Furthermore, the present base of the basalt shows all the characteristics of the fine-grained chilled margin of the flow.

(*e*) Finally, with a view to obtaining the best positive evidence, a trench was dug at the western extremity of the Orval lavas to expose the granophyre-basalt contact. The actual contact was found under two feet of drift some thirty feet below the lowest near-by natural exposure of basalt. Specimens were collected from this trench and were examined microscopically.

The crystallinity of the granophyre half an inch below the contact plane is the same as elsewhere, the grain-size being approximately 1·5 mm. The orthoclase is turbid, occasionally to the extent of becoming opaque. The soda-plagioclase is also turbid and decomposed. The hornblende is almost totally decomposed and replaced by an aggregate of limonitic material. No fragments of basic material are found, and no chilled-edge is present.

The basalt two inches above the granophyre is a fine-grained amygdaloidal rock with plagioclase phenocrysts set in a brown glassy groundmass. The amygdules consist of calcite, zeolites, chlorophaeite, and a greenish-brown serpentine. No signs of crystallization of the chlorophaeite or of alteration of the zeolites and serpentine are discernible. The entire rock has obviously suffered no metamorphism.

Between the granophyre and the basalt there is found approximately one inch of a highly decomposed rock. Such specimens as could be sectioned show the rock to be of basaltic composition but to vary widely in grain-size. The amygdule infillings of chlorophaeite and serpentine are all unaltered. This rock has clearly suffered no metamorphism. It is a fragmental deposit derived from basalt but owing to its highly decomposed state a more precise determination of its nature is impossible.

The evidence from the specimens collected from the trench disproves the supposed metamorphism of the basalts by the granophyre. On the other hand, it gives strong support to Judd's hypothesis that the basalts rest unconformably upon an erosion surface cut in the granophyre.

Conclusion

In the foregoing sections considerable evidence has been put forward against the current interpretation that the basalts of Orval were intruded and metamorphosed by the underlying granophyre. The presence of acidic veins and widespread metamorphism, claimed by Geikie, has not been substantiated. Further counter-evidence is found in the absence of xenoliths, the constant ferromagnesian content

of the granophyre at all distances from the contact and the absence of a fine-grained margin in the granophyre.

Two further items of evidence are given which seem to call for a return to Judd's interpretation—the occurrence of an unmetamorphosed fragmental deposit consisting mainly of basalt at the base of the Orval lavas, and the existence of a chilled margin at the base of the lowest basalt on Orval. Furthermore, the rapid variation of the thickness of the basalt lavas of the region calls for an explanation.

The following time-sequence is in accord with all the evidence now available :—

(*a*) The granophyre was emplaced as part of the Tertiary plutonic complex of Rhum.

(*b*) Erosion exposed the granophyre, and an east-to-west river valley was cut in the rock. This river valley was slightly to the north of Orval, thus accounting for the northerly slope of the granophyre surface.

(*c*) Several basalt lavas flowed into this valley. In the earlier stages of this vulcanicity the lower part of the valley was filled by basalt, leaving the higher slopes of granophyre still exposed. The detritus subsequently supplied to the river would then naturally consist of commingled basaltic and granophyric material. Relics of this are now found as the " basaltic conglomerates " of Rhum and Canna (Harker, 1908, pp. 39–52).

(*d*) Further eruption of basalts continued until the valley was completely filled with lava, and the river was forced to cut a new channel through the lava plateau. The location of this new channel in the western part of the Isle of Rhum was some little distance to the north of the original river valley. As a result of the formation of the new river course, the basalt lavas were removed from the central and northern parts of the old river valley but remained on the southern slopes, although much diminished in thickness in places. The erosion of this new river valley is thus the cause of the variation in thickness of the basaltic lavas now seen on Orval and Fionn-Chra, and of the absence of basalt from Bloodstone Hill. Orval was definitely on the south bank, Bloodstone Hill was in the middle of the valley, and Fionn-Chra occupied a level intermediate between the two.

(*e*) Into the later valley was erupted a sufficient thickness of mugearite to cover at least part of the remaining basalt. The remnants of these flows are now seen on Fionn-Chra and Bloodstone Hill.

(*f*) Further erosion during the Tertiary and Quaternary periods eventually produced the topography of the area as seen to-day.

ACKNOWLEDGMENTS

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GRANT INSTITUTE OF GEOLOGY,
UNIVERSITY OF EDINBURGH.

Lineation and its relation to sub-crustal Convection Currents

By E. M. Anderson

(PLATE III)

Abstract

A possible cause of the lineation developed in the Scottish Highlands and elsewhere may consist in the presence of sub-crustal convection currents. While it is recognized that these are, to some extent, conjectural, the probable results of the conjecture are compared with the directions of lineation, in areas where this structure has been investigated.

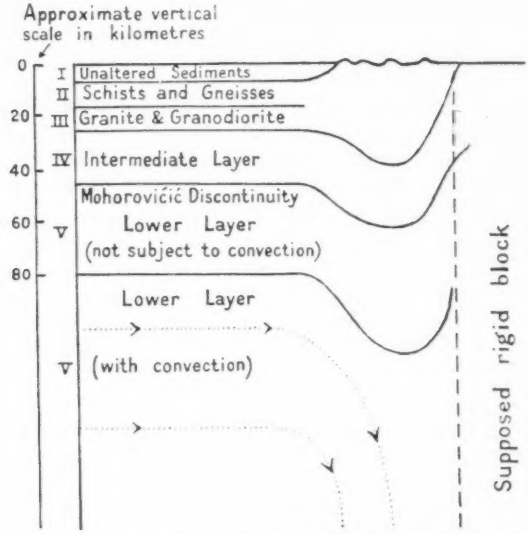
THAT lineation may be of more than one variety has been shown by E. Cloos (1946). It should therefore be stated that what will mainly be dealt with is what has been defined as the Tummel Type (Anderson, 1948). The opportunity will, however, be taken slightly to broaden the definition. This variety was originally restricted to schists, etc., in at least as high a state of metamorphism as Barrow's garnet zone. It seems, however, that a more satisfactory criterion would be that the schists in question should be "tectonites", that is, show petrofabric figures when studied with a revolving stage under the microscope. The figure would, in the majority of cases, be a girdle normal to the lineation, when the latter was present. As corrugated mica will always show an incomplete girdle in this plane, it is necessary to exclude this mineral, and base the new definition on other mineral species, and especially quartz. Subject to the new criterion, the presence of garnet would be unnecessary.

The existence of convection currents is, of course, still a matter of conjecture, and the same must apply to all the conclusions of this paper. Their presence is, however, often assumed to be one of the possible causes of the origin of mountain ranges. If this is the reason, they must, at a distance from the mountain belts, be more or less horizontal, running towards, and more or less perpendicular to, the ranges in question. Nearer the mountains they steepen, and beneath the actual orogenic areas they plunge downwards into the depths. The more resistant material, above the convective layer, sinks here so as to form mountain roots. It is perhaps the presence of the roots, before the elevation of the chains themselves, which has caused the strips of negative anomaly, such as that of the Sunda arc.

A supposed section through a mountain range is shown in Text-fig. 1. For simplicity it is assumed that one is dealing with a two-dimensional problem and that the section would be the same in any plane parallel to the diagram, which is itself normal to the axis of the mountains. It shows, in any case, only one variant among possible examples of orogeny, where there is unilateral convection, the opposite side of the

diagram being occupied by a rigid, or " Pacific " block. Other variants are possible, and one in particular, which is perhaps the type exemplified in Britain, will be referred to in a future paragraph.

It is, of course, in the layer numbered II, which includes schists and gneisses, that most observations of lineation have been made. As convection currents can only occur in homogeneous media, their upper limit cannot be higher than the Mohorovičić discontinuity,



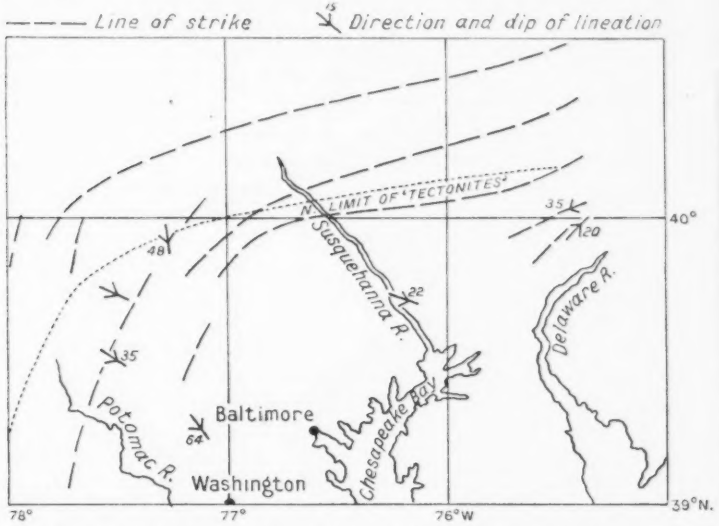
TEXT-FIG. 1.—Cross section showing layers of crust, and convection, near mountain chain.

separating layer IV from layer V. This break occurs at an average depth perhaps of 40 kilometres, at a distance from any mountains. It is supposed that layer V consists entirely of some type of ultrabasic rock. Gutenberg has, however, inferred that there is a transition from crystalline to non-crystalline material at about 80 or 100 km., and that this causes a shadow-zone which is relatively unaffected by earthquakes. As the evidence for this seems strong, the upper limit of convective movement has been taken, although somewhat reluctantly, at 80 km. from the surface. It would have suited the deductions of this paper much better if it could have been assumed to be the Mohorovičić discontinuity.

As far as the writer is aware, no change of state or composition has been proved to exist between that last mentioned and the " Jeffreys-Bullen " discontinuity, at about 475 km. The vertical range

of the currents may therefore be taken to be at least some hundreds of kilometres.

Along some line, such as one of those shown by arrowheads in Text-fig. 1, horizontal movement must rise to a maximum. Above this it must decrease, or, in other words, there must be shearing movements, and shearing forces, probably more or less parallel to the maximum current below. If one is not near the mountain axis, these



TEXT-FIG. 2.—Strike and lineation in part of Appalachian Mountains.

will be nearly horizontal, and, according to an elementary principle, they cannot cease abruptly where the crystalline material is reached. Movement will depend in part on the elastic constant μ, which remains finite, although it may be a good deal increased in amount.

The theory of lineation here advanced may be stated briefly as follows. Subject to a simple condition, which will be stated in a later paragraph, the shearing force and the movement will be *passed on* from the non-crystalline to the crystalline part of layer V : from the latter to layer IV, from layer IV to layer III, and from layer III to layer II, in which lineation has been most usually observed. Throughout this distance the shear may retain a direction roughly parallel to that of the currents, although it is probably much reduced in amount.

On this theory lineation can obviously be explained, at least on the mountain margins, but only if it is what is usually denoted as an *a* lineation. Such an *a* lineation is, as a matter of fact, a feature of

certain mountain borders. In Text-fig. 2 the writer has attempted to summarize the conclusions of E. Cloos and A. Hietanen (1941), together with those of R. E. Fellows (1943), about a certain part of

TEXT-FIG. 3.—Lineation of Western Highlands.

the Appalachian Mountains. The area surveyed by A. Hietanen will be referred to later ; the results of Cloos and Fellows illustrate the point quite clearly. The lineation is always transverse to the strike, or normal to the axis of the mountains, but it is not usually flat and

has sometimes a rather high inclination. This may be explained in different ways ; among others it may have been noted in Text-fig. 1 that the currents themselves may tend to dip downwards as the line of plunge is approached. This variation will be dealt with further.

In Text-fig. 3 the writer has collected from various Geological Survey sources, including a few of his own, the lineations shown along the western part of the Highlands of Scotland. This map is much less complete than that of Dr. Coles Phillips (1937) but it extends to Loch Tay, and it should be mentioned that the observations in that neighbourhood were made with the aid of a grant kindly given by the Trustees of the Clough Memorial Fund of the Geological Society of Edinburgh.

The collection at least does not contradict an important result which had previously been shown by Phillips. Along an outer border, coinciding, perhaps by chance, more or less with the Moine Thrust, the direction is inwards, towards the Caledonian axis. Farther east the lineation has a tendency to veer round and become more nearly north and south. On an outer fringe, however, there is the same transverse arrangement which has been noted in the Appalachians, and here, at least, the lineation may be parallel to the inwardly-directed part of the supposed underlying convection currents.

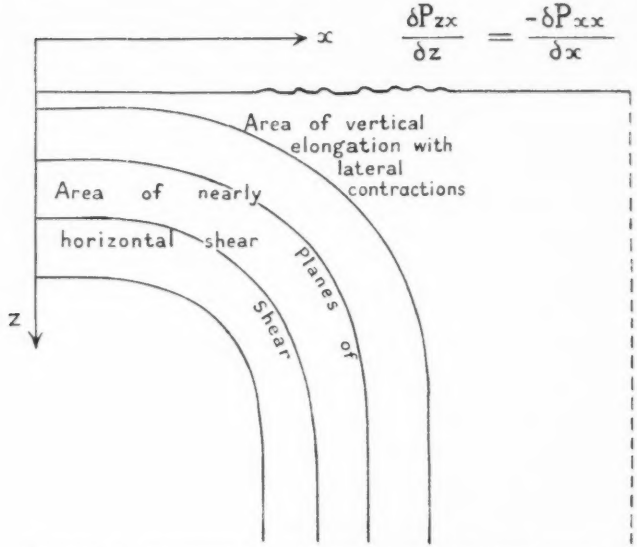
In the Bryn Mawr district, north of the Delaware River, which was investigated by A. Hietanen, lineation is parallel to small folds, themselves in the direction of the Appalachian axis. This area is not marginal but its relation to those described by Cloos and Fellows cannot be clearly made out in Text-fig. 2.

In Scotland it must be emphasized that in most of the western Highlands the structure is extremely irregular and that in many parts it would be wrong to speak of a Caledonian strike. There are, however, areas where lineation and strike both run north-east or north, and one of these occupies all the schistose part of the Shetland Islands. Another occurs to the south-east of Loch Treig, and may extend to Glen Garry and Loch Tay, although within these limits there is evidently some interruption.

In a communication to the *Geological Magazine* (1951) D. B. McIntyre reports that north-east and south-west trends of lineation are characteristic of three main areas in the Highlands : (1) from Kintyre north-eastwards to beyond Fort William ; (2) from Loch Lomond east-north-eastwards along the southern edge of the Highlands to Stonehaven, and (3) along the southern coast of the Moray Firth. While not questioning these results, a glance at Text-fig. 3 shows that such a generalization does not tell the whole of the story. It should also be recorded that a specimen from near the south-west end of Loch Tay, which shows pronounced lineation, and must be included

in McIntyre's Zone 2, is different from those of other areas in type. The corrugations are here much broader, in relation to the size of the mica flakes, and there is an absence of any petrofabric structure in the quartz constituents. The lineation is therefore not here of the " Tummel Type ", defined by the writer.

In general it has been shown that there is a marginal belt of relative


x
$\frac{\delta P_{zx}}{\delta z} = \frac{-\delta P_{xx}}{\delta x}$
Area of vertical elongation with lateral contractions
Area of nearly horizontal shear
Planes of Shear
z

TEXT-FIG. 4.—Suggested dynamics (transverse to length) of assymetric mountain chain.

simplicity and, nearer to the mountain axis, a district of greater complexity with regard to the lineation. This statement certainly applies to Scotland, and probably also to the Appalachians. A lineation parallel to the axis does not, in either case, appear to be confined to one definite belt.

The complexity may conceivably be effected as follows. In the central parts of mountain ranges the supposed currents may be affected by the neighbourhood of a " Pacific block ", or because they impinge upon the mountain roots. Either of these agencies might cause them to turn aside, for a certain distance, and run more or less horizontally before they descend into the depths. This tendency might be reflected, at a higher level, by a change of direction in the lineation. The suggestion is, in any case, admittedly conjectural. It appears to be more certain that the strike has, in many cases, been influenced by

subsequent movements. An instance where strike and lineation appear to have been altered by the same later movement has been described by the writer (1915).

Text-fig. 4 is intended to show not the *directions* or shear but a cross-section of the *surfaces* of shear in the solid part of the crust, overlying the currents, and extending downwards into the (unrepresented) roots. It is assumed, as before, that there is two-dimensional movement. In schistose country the shearing surfaces will correspond roughly to the foliation, and they will *contain* the directions of shear or, in other words, the lineation. If, however, there is any tendency to horizontal movement the lineation may have a large horizontal component, normal to the plane of the diagram. Such a component might cause the lineation and the strike of the foliation to be approximately parallel. There would not, if this were the case, be any proof of a *b* lineation.

Where the structure is two-dimensional, as supposed, and x and z are related as shown in the diagram, one derives the formula

$$\frac{\delta P_{zx}}{\delta_x} = -\frac{\delta P_{xx}}{\delta_z}$$

from elementary dynamical theory. Here P_{zx} represents the shearing stress communicated from below, in the x direction, across any horizontal plane or, in fact, the lineation stress with which one has, to a large extent, been dealing. P_{xx}, taken negatively, means the horizontal pressure in the same direction. (This notation, although not always adopted, is simple, and suits the present purpose.) The equation then serves to illustrate the following relation. As P_{zx} increases in the downward direction, being greatest in proximity to the currents, and zero at the surface, the horizontal pressure must, in such a case as that of Text-fig. 4, increase from left to right.

The writer believes this to be a point of some significance in the structure of the Caledonian chain. It is indicated in the diagram by naming one part as " Area of vertical elongation, with lateral compression ". The intention is to suggest that the horizontal pressure is here the significant feature, and relieves itself not only by compression across the mountain chain but upwards, after a certain stage, by the elevation of the mountains, and downwards by the formation of roots.

The left-hand part of the diagram has been denoted as " Area of nearly horizontal shear ", and indications show that there are two strongly contrasted types of folding in Scotland. One may, for instance, compare Strath Oykell, with its highly-developed lineation, with the Loch Awe Nappe, particularly near Tayvallich. At the latter locality the vertical elongation of pebbles was noted by the writer in 1903 and

has since been admirably demonstrated by Geological Survey photographs. Here lineation, at least of the Tummel Type, is entirely absent, and the photographs referred to include C 974 Scotland (reproduced as Plate III), C 1007, C 937, and others. The geology of the Tayvallich area can easily be explained in terms of vertical folding, and it may be noted that the schists are here in a much lower state of metamorphism than those of Strath Oykell.

It is not to be expected that the different areas have very definite boundaries, but rather that they will merge into one another, while it has to be remembered that in Text-fig. 4 " area " denotes area in cross-section, normal to the mountain trend. Such an " area " may, however, correspond to an area at the surface, and it is possible that the vertically elongated " area ", while thinning out, passes to some extent over the top of that with horizontal shear, and that the differences mentioned may be explained by differences of level in the crust. The first will probably reach its maximum thickness immediately above the mountain roots. It should not, however, according to the dynamics of the subject, be rigidly confined to this region, and it seems probable that it spreads in the one direction, as has been indicated, and in the other direction to some extent over the " rigid block ", if such is present.

It has long been realized that the Loch Awe Nappe, to which the Tayvallich examples belong, lies at a high structural level. Eastwards, the writer thinks, it is now admitted that it structurally overlies the Ardrishaig Phyllites, if the latter, indeed, should not be regarded as forming a part of it. The phyllites, in turn, must overlie the schists of the Cowal area, where Clough has advanced evidence of the presence of " rodding ", or lineation (1897). This lineation probably belongs to McIntyre's belt No. 2.

It is therefore quite probable that in this part of Scotland a formation with vertical elongation and, it should be noted, Caledonian strike, overlies another which, although it has also in parts a Caledonian strike, has not the vertical elongation. In place of the latter there is lineation, which probably points to some degree of horizontal shearing.

For some 50 miles to the south-east of the Cowal area observations are precluded by the fact that beds later in period than the Caledonian orogeny are brought to the surface by the Highland Boundary Fault. Where Ordovician strata become visible, in Carrick, and south-east of the Glen App and Southern Boundary Fault, they show a fairly persistent Caledonian strike, which extends over the whole width of Scotland and is a feature of the entire Southern Uplands, apart from areas of granite, and those which are covered by later formations. In all this distance there is no trace of lineation. In the very numerous cross-sections of different parts of the Uplands which have been made

by Peach and Horne the folds show a tendency to what has been called " concertina structure " (1899). The same bed may be repeated over wide areas by isoclinal folds dipping sometimes as much as 45°, but showing, on the whole, a preference for their axial planes to be nearly vertical.

This is not what one might expect if there was any great degree of underlying horizontal shear, but suggests rather the type of folding which has been found near Tayvallich. It cannot be doubted that the area as a whole has been horizontally compressed in a direction normal to the strike. Vertical elongation is not, however, here shown by the elongation of pebbles. Concertina folding may be the indirect result of the same conditions, although this theory can only, at present, be made as a suggestion and the process seems somewhat obscure.

In the Lake District folds and strike run in general east-north-east, nearly parallel to those of the Uplands. The plications seem, on the whole, not to be so pronounced, and are complicated by the presence of at least one large thrust, as well as by the supposed " lags " of J. E. Marr. It should be noted, however, that Marr, in writing about this district, believed that it had been horizontally compressed, while he did not exclude the possibility of a vertical elongation (1916, p. 73).

In large parts of Wales the Caledonian strike persists, although it has a tendency to irregularity, and dies out gradually to the east or south-east. It certainly extends to Wenlock Edge, and to Ludlow, but probably not to the Woolhope Inlier or to the Malvern Hills.

A good deal might, of course, depend on the depth to which erosion has extended in any of the districts which have been mentioned. An example of this has been afforded by the Loch Awe Nappe, viewed in its relation to Cowal. It seems, nevertheless, that of the two very distinct types of folding in the Caledonian mountains of Britain the relations depend less on depth of formation than on geographical position. Speaking broadly, this orogenic belt appears to have two contrasted borders, as follows :—

(1) A west-north-western or north-western border, in which the folding is due to more or less horizontal shearing developed, as we assume, rather directly by underlying convection currents. This covers a great deal of the western Scottish Highlands, and

(2) a south-eastern border where the folding is of the " concertina " type and there is horizontal compression normal to the strike with, in places at least, vertical elongation. This extends throughout the Scottish " Southern Uplands " and includes the Lake District and a large part of Wales. This type of folding may also be caused by convection currents, but in an indirect manner, as has been explained above.

The north-western border may, as has been suggested, overlie a part

of the convective layer. It is probable that the south-eastern border directly overlies the mountain roots, although it overlaps to some extent the area of lineation.

It is difficult to suppose that the British and Scandinavian Caledonids as a whole are assymetric, and adjacent, as in Text-fig. 1, to a rigid or "Pacific" block, which might be supposed to extend to the east or south-east. The observations of Strand (1945) and Kvale (1945) seem to show that there is an area in Norway where there is shearing motion such as might be caused by convection currents running west or north-west, that is, in the direction opposite to what has been assumed in Scotland.

If two sets of convection currents, belonging to different "cells", met head on before descending into the depths the results might not be very different from what has been observed near Bergen and Bygdin, on the one hand and, on the other hand, in the Highlands. The two opposing sets might cause, and be separated by, an area of lateral compression, with vertical elongation such as has been suggested in Text-fig. 4. This belt might include in its course the Scottish Southern Uplands and possibly continue somewhere to the west of Bergen, perhaps hidden under the sea. This, it is admitted, is highly conjectural and there is a still greater difficulty in accounting for the absence of any counterpart of the Norwegian movement in the Woolhope Inlier and in the Malverns where the vertically folded belt appears to have died out to the south-east.

If the suggestion is true the British–Scandinavian mountain range may be, to some extent, symmetrical. The assymetrical type, roughly represented in Text-fig. 1, appears also to occur and to be at present in process of formation, notably along the borders of the Pacific. Here Gutenberg and Richter have in many parts recorded their zones (A) to (F), or parts of the sequence, extending inwards from the ocean, while there are no counterparts on the opposite side. (A), where recorded, is always the fore-deep, and (B) the zone of negative anomalies which presumably corresponds to mountain roots but only locally rises above sea-level (1945). Where it does, as in the island of Timor, Umbgrove has shown that there has been recent Tertiary folding (1947). The data are troublesome to reconcile with any theory of convection currents, and Gutenberg and Richter have not tried to do so. They do not, however, necessarily disprove what has been said about Norway and Scotland.

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VERTICAL ELONGATION OF PEBBLES IN CONGLOMERATE. 2¾ MILES S.W. OF TAYVALLICH.

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[*To face p.* 122.

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The Moinian Inlier of Rosses Point, near Sligo, Eire

By G. G. Lemon

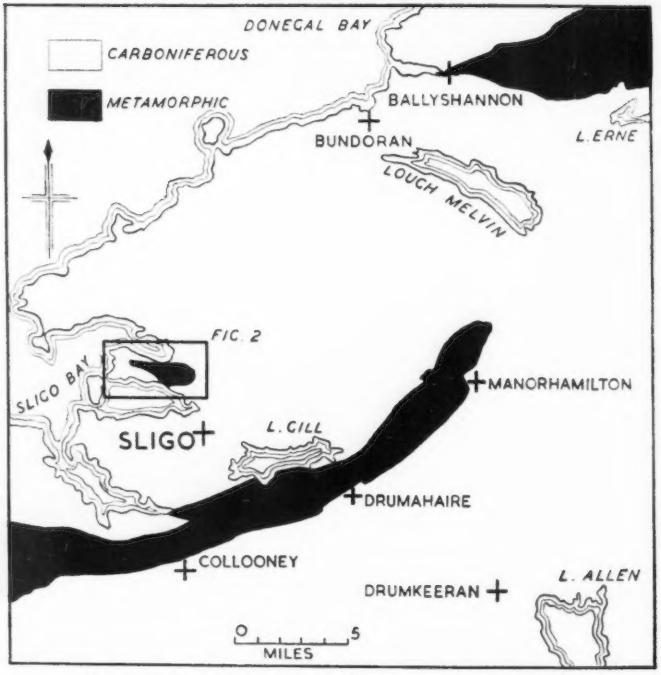
Abstract

The following note provides the first detailed description of an inlier of metamorphic rocks occurring in the core of an anticline of Carboniferous Limestone at Rosses Point, three miles north-west of Sligo.

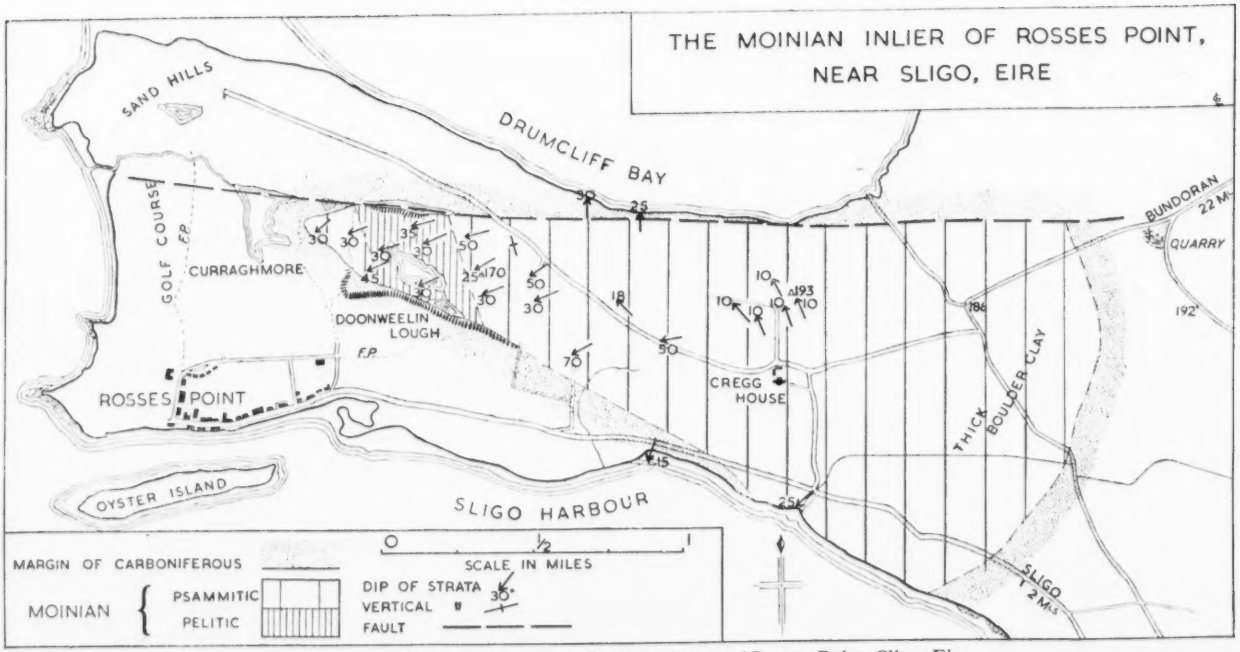
The metamorphic rocks are shown to belong to the kyanite zone ; comparison with the Lough Derg area suggests a Moinian Age.

Introduction

THE presence of the inlier at Rosses Point, near Sligo, has long been known, as it is shown on Griffiths' Geological Map of Ireland (1838) and mentioned by Wynne (1864) and by Hardman (1882). Its boundary is depicted on Sheet 42 of the 1 inch to the mile Geological Map of Ireland ; in the relevant Memoir (Wynne, 1885, p. 14) the rocks of the area are described as gneiss, schists and



Text-fig. 1.—Geological sketch map of the Sligo district.



TEXT-FIG. 2.—Geological map of the Moinian Inlier of Rosses Point, Sligo, Eire.

quartzites of Archean Age. Brief reference is also made by Cole (1913).

The author mapped the inlier in the summer of 1951, and would like to thank Professor J. G. C. Anderson for drawing his attention to the area, and also to acknowledge the facilities extended by the Geological Survey of Ireland for the examination of original 6-in. maps.

Field Description

The metamorphic rocks are exposed in the west and centre of a small triangular area, which extends for about 2½ miles in an east–west direction along Rosses Point promontory (Text-figs. 1 and 2). The eastern end of the inlier is obscured by drift, and it is possible to draw only a tentative boundary.

The inlier forms relatively low, rough, boggy ground, covered with heather and scrub, which is in marked contrast with the well cultivated fields underlain by the surrounding limestone.

Good exposures are seen at the western end (Text-fig. 2) in scarp faces with a generally easterly aspect. Other exposures occur north and south of Cregg House.

The rocks of the inlier are predominantly psammitic, with minor pelitic or semi-pelitic bands which vary from 1 inch to as much as 2 feet in thickness. These pelitic layers tend to be concentrated in the western exposures of the inlier, so much so that a distinct pelitic belt can be mapped ; this merges into the psammitic rocks on both sides.

The psammitic rocks weather to a light grey colour and are characterized by the many thin yet conspicuous dark bands formed by biotite-rich layers. Weathering along these micaceous laminae gives these psammitic rocks a flaggy appearance which is particularly evident in strike sections.

The pelitic members tend to be soft and crumbling due to weathering and form depressions in the more resistant psammitic rocks.

Both psammitic and pelitic members of the inlier are abundantly veined by quartz, in bands from ⅛ in. to 1 foot in thickness. These quartz veins are, on the whole, parallel to bedding surfaces.

In two exposures within the pelitic belt small lenticular patches of pegmatite were observed. These pegmatites are characterized by large quartz and oligoclase crystals, and by the abundance of rosettes or " books " of muscovite, up to 1½ inches across. No microcline was detected in thin sections of these pegmatite patches. Tourmaline is especially conspicuous, standing out from the weathered surfaces. This mineral was not detected in the schists.

Petrography

Psammitic Rocks.—In thin section the psammitic rocks show a

markedly granoblastic structure. These psammitic rocks are essentially quartz-mica-granulites, the characteristic minerals being quartz, mica, garnet, and microcline and oligloclase felspar.

The equidimensional quartz and felspar crystals possess irregular sutured boundaries, with the micas sparsely distributed throughout the rock. Any tendency towards parallel orientation of the minerals is poorly expressed, being most evident in the more micaceous bands. Biotite is the more characteristic mica, muscovite being more noticable where microcline is abundant.

In the more easterly exposures of the psammitic rocks the dominant felspar is microcline. Oligoclase is next in importance while orthoclase is rather scarce. In the westerly exposures there is a marked decrease of microcline in favour of oligoclase.

The proportion of microcline to oligoclase does not exceed a one to one ratio, while quartz is about four times as abundant as the combined felspars, with the exception of the more microcline-rich granulites. In the latter the quartz-felspar ratio is about three to one.

Small and irregularly shaped garnets are scattered sparsely throughout the psammitic rocks. The garnets increase in size and their boundaries become more regular in western exposures. Where microcline is abundant garnet is especially scarce. Kyanite occurs sparingly in the granulites but is more plentiful in the pelitic rocks (see below).

Two exposures in the psammitic group yielded evidence of originally calcareous bands. These bands tend to be weathered a lighter colour than the surface of the normal siliceous granulites. One exposure is characterized by the presence of hornblende, the other by zoisite. Associated with these minerals, in both exposures, are abundant idioblastic crystals of sphene. Calcite is also present in small amounts.

Pelitic Rocks.—The pelitic belt is characterized by highly micaceous, garnet-rich, quartzose schists. The conspicuous garnets stand out from weathered surfaces and reach a diameter of 1 cm. in some cases. Oligoclase is the dominant felspar, microcline being generally absent. Quartz grains are much more abundant than felspar.

The most significant feature of these pelitic schists is the presence of kyanite. This mineral is not, however, abundant, being found in only a few exposures and in certain thin layers ; in some cases the crystals attain a length of 2 cm.

Despite the highly schistose nature of the pelitic layers the idioblastic garnets are not as a rule cracked or distorted in any way. The garnets clearly push aside mica laminae and must have formed after most of the schistosity had been imparted. One thin section shows garnets which were rotated while forming, enclosing quartz grains in the process. In this particular thin section the garnets are also breaking down into chlorite along cracks and around the crystal boundaries.

Structure

No reliable examples of current or graded bedding were found from which the original order of deposition could be determined. Flow-cleavage in micaceous layers sandwiched between psammitic beds in the pelitic belt shows these beds to be right way up, but such structures are not sufficiently widespread to be of general use. No satisfactory conclusions can therefore be drawn regarding the pre-Carboniferous tectonics.

The inlier is brought to the surface by an anticline in the middle-Carboniferous Limestone of Rosses Point. This anticline has a gentle pitch westwards with apparently a flattening towards the east. A vertical strike fault on the northern limb makes a marked feature running almost the whole length of the promontory. The fault lies in a lough-filled depression in the west, producing a scarp in the schists and granulites, which becomes obscured by drift in the east. The east–west folding and faulting is probably of Armorican date, like that of the Ballyshannon area to the north (Anderson, 1948).

Comparison with Other Areas

In their appearance in the field, in hand specimen, and in thin section the metamorphic rocks of the inlier closely resemble those of the Lough Derg area to the north. Evidence that the Lough Derg rocks are of Moinian age has been put forward by Anderson (1948). It appears likely, therefore, that the same rocks form the basement of the Carboniferous Limestone in a large area south of Ballyshannon.

Metamorphic rocks, which Anderson (1948, p. 187) suggested might be of Moinian age, also form a long outcrop south-east of Sligo (Text-fig. 1). These are being examined by the present writer between Manorhamilton and Collooney.

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Department of Geology,
University College, Cardiff.

Magmatic Intrusions and Lava-sheets in the Raman area of the Nagev (Southern Israel)

By YAACOW K. BENTOR

(PLATE IV)

ABSTRACT

Southern Israel is traversed by a series of north-easterly trending anticlines, the largest of which is the Raman anticline. Here a deep erosion-cirque exposes a sedimentary succession from the Cenomanian down to the Triassic, including a series of magmatic rocks of highly alkaline affinities. The forms of these magmatic bodies are described in detail and from their field-relationships with the sediments it is shown that they include a stock, a laccolith, sills, dykes, and a basaltic flow. This igneous activity took place between Lower Triassic and Upper Jurassic times and was perhaps restricted only to the Jurassic. Comparison with the surrounding areas leads to the conclusion that the Raman region was the centre of magmatic activity during this period.

INTRODUCTION

THE southern part of Israel, known as "The Negev", is a desert region of about 10,000 sq. km. built up mainly of Cretaceous and Eocene strata. A series of anticlinal ridges with a general north-east trend crosses the area, and it is only in the higher ones that formations older than the Cretaceous are exposed.

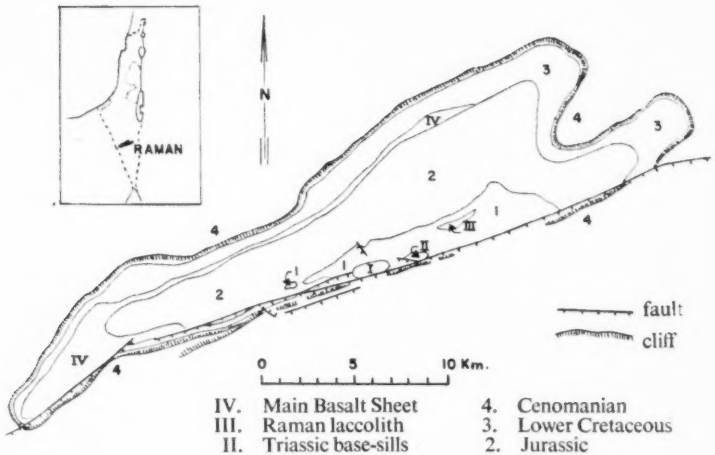
The largest of these tectonic belts is the anticlinorium of Raman; in its highest part, which lies more than 1,000 m. above sea-level, a deep erosion cirque has been developed exposing a rock sequence down to the Triassic. In this region the occurrence of magmatic rocks was discovered some years ago by petrologists of the Iraq Petroleum Company, but the published results (Shaw, 1947) gave no details regarding the nature of these rocks or the mode of their emplacement. In the spring of 1950 several weeks were spent studying this area, which covers about 200 sq. km. Work was carried out from camps especially established by the Israeli Army of Defence to facilitate the investigations. Part of this work was devoted to a study of the magmatic phenomena, which from a regional point of view are of great interest; such an assemblage of magmatic rocks is not seen anywhere else in the country apart from Jebel Ureif, 14 km. south of Raman, geologically a part of the same unit.

Both the form and composition of the rocks present some unusual features. This paper will describe the form and mode of emplacement of the magmatic bodies; their detailed petrology will be dealt with later.

1. GENERAL GEOLOGY OF THE AREA

The anticlinorium of Raman extends for a distance of about 90 km. in a north-east to east-north-east direction crossing practically the

whole breadth of the Negev, from the Sinai border in the south-west to near the Dead Sea in the north-east (see inset Text-fig. 1). The maximum upwarp is attained in the region of Wadi Raman. Here, in the culmination area of the tectonic axis, three domal upwarps are superimposed on the simple anticlinal structure. A small distance further east-north-east the axis bifurcates giving rise to two separate anticlines. Throughout the Wadi Raman area the anticlinorium shows



TEXT-FIG. 1.—Erosion-cirque in the region of Wadi Raman.

pronounced asymmetry : towards the north-north-west the strata dip gently at 2° to 5° but towards the south-south-east the inclinations are much stronger, averaging about 70°, and in some places the beds are overturned. The southern flank is cut by a major fault zone with as much as 1,500 m. downthrow to the south. The main faults trend almost parallel to the anticlinal axis and are generally situated a small distance south of it ; in the area of maximum upwarp the faults lie at places slightly north of the tectonic axis.

In the region of Wadi Raman a large fluviatile erosion-cirque is cut into the centre of the anticlinal structure (see Text-fig. 1) ; it is roughly elliptical in form but at its north-eastern end it splits up into two lobes which reflect topographically the bifurcation of the tectonic axis. The longitudinal axis of the cirque trends E.N.E.–W.S.W. parallel to the tectonic axis, but it is situated a few kilometres farther north. The length of the cirque is 40 km. and its maximum breadth is 9 km. The cirque is bounded by an almost vertical cliff 200 to 250 m. high.

This cliff is continuous all around the cirque except at those few places on the southern side where the faults run north of the anticlinal axis. The only passes into the interior of the cirque occur here.

The upper two-thirds of the cliff are composed of predominantly hard rocks of Cenomanian age which overlie the much softer Lower Cretaceous Nubian Sandstone. The latter forms the lower third of the cliff as well as part of the floor of the cirque. Nearer to the centre of the cirque there are extensive Jurassic outcrops.

The three domal upwarps on the southern side of the cirque uncover, moreover, a thick series of Triassic beds. Details of the geological column are given in Table 1.

TABLE 1.—GENERALIZED STRATIGRAPHICAL SECTION IN WADI RAMAN

	AGE	ROCK SERIES	THICKNESS IN METRES	MAIN ROCKS	FACIES
Cenomonian . .		—	403·0	Limestone, dolomite, marl.	Marine
Lower Cretaceous .		—	105·0	Nubian sandstone.	Mainly continental
JURASSIC	Upper Malm (?) .	Upper Nubian Sandstone group Series.	0–51·4	Nubian sandstone.	Continental
	Malm . .	Upper Marine Series	0–46·4	Marl, dolomite, shales, sandstone.	Marine
		Main Nubian Sandstone Series	320	Nubian sandstone.	Mainly continental
	Dogger (?) . .	Lower Marine Series	20·0–74·5	Limestone, marl, sandstone.	Mainly marine
TRIASSIC	Keuper (?) . .	Main Gypsum Series	90·0–174·4	Gypsum.	Lagoonal
	Muschelkalk .	Marl-Limestone Series	170·7	Limestone, marl, some gypsum.	Marine
	Bunter Sandstone .	Shales-Sandstone Series	151·5	Shales, sandstones.	Littoral

base not exposed.

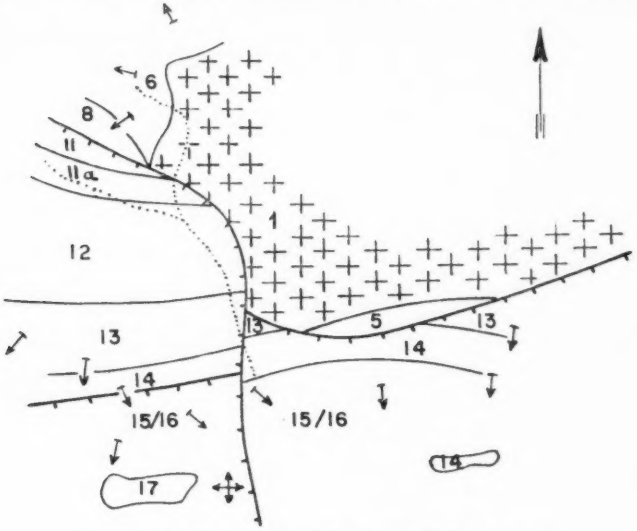
Magmatic rocks occur throughout the whole range of Triassic and Jurassic strata up to the base of the Lower Cretaceous Nubian Sandstone. Notwithstanding the smallness of the area in which they occur, the magmatic rocks of the Raman region are developed in widely varying forms, including a stock, laccolith, sills, dykes, and extrusive sheets.

2. THE MAGMATIC BODIES

(*a*) *Jebel E-Rishe, a hypabyssal stock.*

Jebel E-Rishe rises near the middle of the southern cliff of the cirque. This mountain appears topographically as a ridge towering some 120 metres above the surrounding plain. It has an almost elliptical outline, the longer axis being parallel to the east-north-east

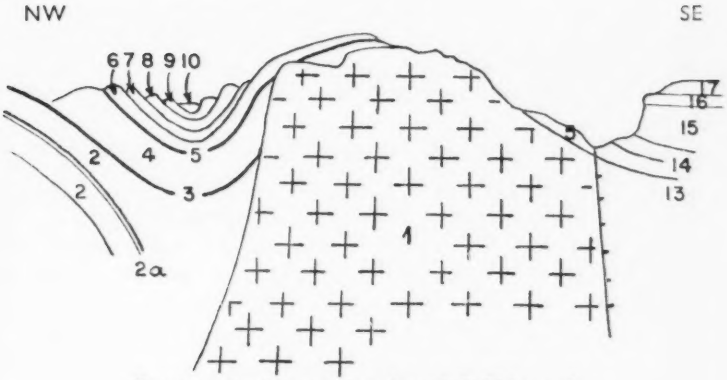
trend of the cirque. It is some 1,800 metres long and 700 metres wide. The relationships to the surrounding strata are rather complicated. The southern and western margins have been subjected to a series of faults whose complexity is related to the strong contrast in the mechanical properties of the hard magmatic rocks and the soft sediments which they invaded. These fault features are much younger than the intrusion and therefore partly mask the original contact



TEXT-FIG. 2.—Sketch-map, S.W. corner, E-Rishe stock.
Scale—1 : 15,000

LEGEND TO FIGS. 2–6

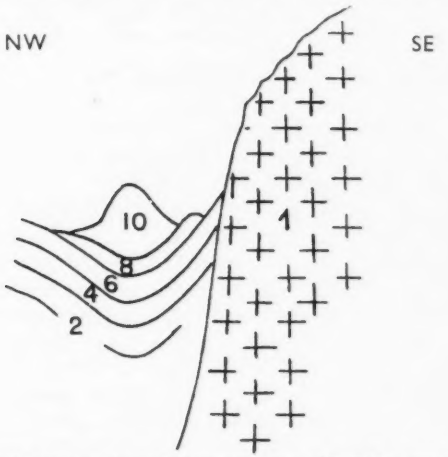
17. Nummulitic Limestone	Middle Eocene
16. Flint	Lower Maastrichtian
15. Chalk	Santonian-Campanian
14. Limestone, Dolomite	Turonian
13. Dolomite, Limestone	Cenomanian
12. Nubian Sandstone	Lower Cretaceous
11*a*. Red Gypseous Clay 11. Main Basalt Sheet	Top Jurassic
10. Nubian Sandstone	Jurassic
9. Shales 8. Upper Quartzite 7. Brown Marl 6. Limestone-Dolomite Series 5. Lower Quartzite 4. Green-grey Marl	Lower Marine Jurassic Series
3. Perlitic Sill	
2*a*. Bituminous Shales 2. Gypsum	Keuper (?)
1. Quartz-syenite (stock).	



TEXT-FIG. 3.—Cross-section through E-Rishe stock.
Scale—length 1 : 30,000
height 1 : 4,000

relationships. Text-fig. 2 gives a geological sketch map of the south-western corner of Jebel E-Rishe. Remnants of Jurassic sediments in direct contact with the magmatic rock are preserved on the lower southern slopes of the stock. It therefore appears that the stock never extended much further south than its present limits.

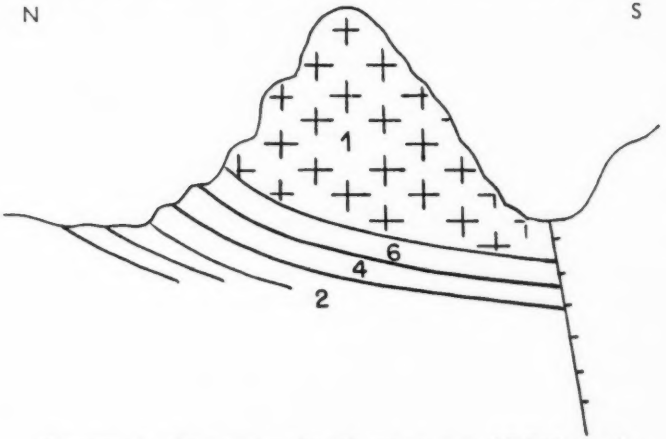
A sharp syncline forms the northern boundary, its axis being parallel to the elongation of the stock (see Text-fig. 3) ; it does not appear,



TEXT-FIG. 4.—Cross-section through northern part of E-Rishe stock.
Scale—length 1 : 30,000
height 1 : 4,000

however, that the intrusion was responsible for the folding. It rather seems that the syncline was formed well after intrusion took place probably during the phase of regional faulting, by the thrusting of the whole sedimentary series from the north against the resistant magmatic block.

The intrusive character of the magmatic body is best seen in the western part. Here its boundary cuts at a sharp angle through a



TEXT-FIG. 5.—Cross-section through eastern part of E-Rishe stock.
Scale—length 1 : 30,000
height 1 : 4,000

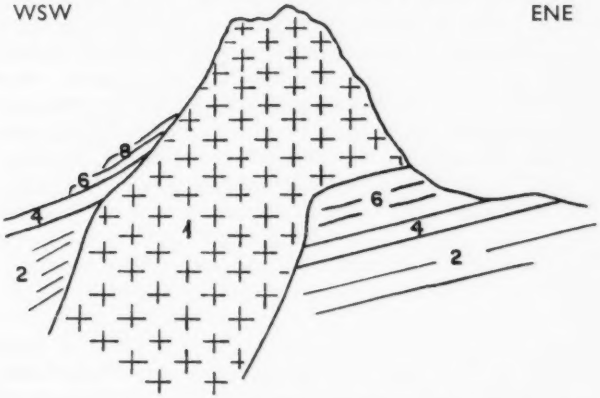
stratigraphical sequence from the Triassic Main Gypsum Series up to the top of the Jurassic Lower Marine Group (Text-fig. 4). Rather different relations appear on the eastern side, however, for there the magmatic rocks are found to overlie concordantly the same lower marine beds of the Jurassic (Text-fig. 5).

Accordingly, the magmatic body of Jebel E-Rishe is best described as a stock of nearly circular form, 700 metres in diameter, penetrating the sedimentary sequence at least to the level of the Jurassic Lower Marine Series. A thick sill-like apophysis protrudes out of the stock towards the east and penetrates the sediments near the top of the Jurassic Lower Marine Series ; details of this relationship are shown in Text-fig. 6.

The intruded strata, as far as they are still preserved around the upper flanks of the igneous mass, dip as a rule strongly away from the stock. This seems to indicate that at least in the later stages of its injection the magma cleared room for itself by a doming up of the surrounding strata. The question therefore arises whether the magma

ever actually pierced the surface ; but as the whole sequence of rocks younger than the lower Marine Jurassic series is preserved in the vicinity of the stock without any comparable magmatic rocks amongst them, it appears more likely that the intrusion stopped at a short distance from the surface.

This magmatic body has been formed by a single intrusive act and is composed of the same rock-type throughout, yet with many textural and even some chemical variations. Thus the centre is formed of a coarse-grained, highly alkaline quartz-porphyry of nordmarkitic affinities which passes, towards the contacts, into a fine-grained to almost aphanitic rock, with or without orthoclase phenocrysts.



TEXT-FIG. 6.—Generalized cross-section through E-Rishe stock.
Scale—length 1 : 30,000
height 1 : 4,000

(*b*) *The Raman Laccolith.*

Five kilometres north-east of Jebel E-Rishe there occurs another intrusive mass, but in contrast to the predominantly discordant relationships of the E-Rishe stock, this body has been concordantly injected and can be described as a true laccolith. It has been intruded within, and near the top of, the Main Gypsum Series of Upper Triassic age. Gypsum must surely be a rare country rock for a laccolithic intrusion !

The Gypsum Series dips towards the north-north-west at 3° to 4° and has been eroded together with the laccolith to an almost horizontal plane. In its central part the laccolith attains a thickness of some 60 metres, thinning abruptly to the south-west ; to the north-east, on the contrary, its thickness decreases slowly. The whole form is therefore asymmetrical. Its maximum length is 4 km.

In form the laccolith is curved at its base as well as along its roof, roughly resembling a biconvex lens ; to this shape the Gypsum Beds conform throughout, having been pushed apart and warped downwards as well as upwards. This warping is clearly visible in the air photograph (Plate IV).

The whole laccolithic mass has been emplaced in one intrusive act and therefore shows uniform composition with, however, large textural variations ; the rock is best classified as an essexite. In the central part of the laccolith it is very coarse-grained, but unfortunately here it is badly weathered. Strewn over the whole area are innumerable weathered-out pyroxene crystals up to 1 centimetre across. Towards the margins the rock becomes progressively finer in grain until it passes into a microcrystalline variety containing large plagioclase and pyroxene phenocrysts. A special feature of this rock throughout all its textural variations is an abundance of sulphide minerals.

The whole mass is traversed by numerous dykes trending mostly west-north-west, some of which are of a related rock type, others representing younger intrusions of different magmas.

The gypsum beds above and underneath the laccolith are clearly affected by contact-metamorphism. The white and soft gypsum has been baked into a black, hard, splintery rock ; this effect extends only a few decimetres from the contact.

(*c*) *Sills.*

There is a very large number of sills exposed in the Wadi Raman. They range in composition from basaltic to syenitic and occur in every formation from the base of the exposed Triassic to the top of the Jurassic. Some of the sills are simple whereas others are composite ; they vary in thickness from a few centimetres to 15 metres. Whereas the distinction between sills and surface flows is not always easy, some of these bodies show features which place them undoubtedly into the category of intrusive sills. Thus the large syenitic sheet occurring within the Jurassic Lower Marine Series, which is exposed near the southern passageway from the cirque, has clearly produced contact metamorphism in the adjacent shales on the upper as well as on the lower surfaces of the sheet. These shales have been transformed into a dark brown, glassy, splintery calcareous hornfels containing numerous druses lined with quartz and calcite crystals.

Another line of evidence is furnished by many of the sheets which are exposed on the slope of the main Wadi Raman. Thus the sheet occurring 1,200 metres north-west of the point where the Wadi Raman escapes from the cirque shows actual transgressions. This sheet is 2½ metres thick and lies within the upper part of the limestone-marl series of the Muschelkalk, which is composed of alternating shale,

limestone, and gypsum beds. The sheet is generally seen following a particular bedding plane between two limestone bands ; but at one point it suddenly plunges down from this level, piercing the underlying limestone band until it meets the boundary with the lower shales. It follows this bedding plane for a few hundred metres only to regain by a similar transgression a level somewhat higher than the original one. During the actual transgressions the thickness of the sill decreases but the former value is immediately restored on a return to the horizontal position. The passage from one horizon to another lying about 2 metres deeper is effected over a horizontal distance of less than half a metre. The zone of contact-metamorphism follows closely this zig-zagging of the sill but is better developed against the shales than the limestones.

Similar features are seen in many of the concordant sheets in Wadi Raman. In all these instances, therefore, there can be no doubt that these sheets were emplaced by a sill-mechanism.

A special case is presented by the two large " Triassic basal-sills ", which occur 3·7 km. east-north-east of Jebel E-Rishe in the anticlinal core of Wadi Raman. These rocks are lying conformably within the Triassic shale-sandstone series, and represent the lowest horizon exposed in the whole Wadi Raman. The higher mass has a thickness of 8 metres and is over- and under-lain by variegated shales. The lower mass occurs 16 metres deeper but its base is nowhere exposed ; in the erosion cliff at its eastern end it is seen to be at least 68 metres thick.

These two masses are composed of the same rock, a grey to violet, fine-grained trachytic type ; in chemical composition they are very close to the Jebel E-Rishe rock although even a little more alkaline (leuco-evisitic magma-type). Rocks of this composition are encountered nowhere else in the whole area and it is therefore most likely that the formation of these Basal Triassic Sheets is genetically connected with the intrusion of the Jebel E-Rishe stock. As the stock pierces Jurassic strata these related sheets found in the Lower Triassic must be intrusive, that is to say, sills. If this is the case then they are the largest of all the sills in Wadi Raman.

(*d*) *Dykes.*

Numerous dykes traverse the succession of rocks up to the base of the Lower Cretaceous Nubian Sandstone. Most of them are simple but some are composite ; in composition they are mostly basic, some dykes of even a picritic nature having been found in the Triassic Gypsum Series. They vary in thickness from $\frac{1}{2}$ to 2 metres.

The area richest in dykes is situated north of the outlet of Wadi Raman ; here, within the Jurassic Lower Marine Series and in the

overlying Main Nubian Sandstone Series, a very large number of dykes can be observed belonging to two prevailing systems the one trending north–south the other roughly east–west.

Conspicuous topographical features are formed where dykes have been weathered differently from the intruded country-rocks : thus, narrow erosion-troughs are found where dykes cut resistant limestones, and conspicuous ridges occur on an otherwise smooth surface where they cut soft sandstones.

Some of the dykes are probably connected with sills of comparable compositions ; others, especially in the western part of the cirque, are clearly feeder dykes of the basalt sheets to be mentioned in the next paragraph ; still others stand independently showing no apparent relationship to other magmatic bodies. The dykes, as well as most of the sills, show abundant signs of large-scale assimilation of the country-rocks.

(*e*) *The Main Basalt Sheet.*

The largest magmatic manifestation in the whole area is a sheet of alkali-basaltic rock directly underlying the Lower Cretaceous Nubian Sandstone. It can be followed as a band along much of the base of the northern cliff, but towards the east it ends rather abruptly 6 km. west of Ras Irdeihi, the mountain rising at the point of bifurcation of the cirque. Along the southern cliff the basalt sheet can be followed eastwards up to the foot of Jebel E-Rishe but on this side it is faulted at many places.

The band has an average thickness of 6 to 10 metres but thickens enormously in the western corner of the cirque up to at least 120 metres ; the many hills up to 100 metres high situated here are composed entirely of basalt. Another less pronounced thickening up to 50 metres is observed on the north cliff just before the sheet dies away in the east.

Over most of its outcrops the basalt shows a beautiful prismatic jointing. The sheet is composed of a black, compact, alkaline basalt, in places rich in olivine phenocrysts.

Directly on top of the sheet, separating it from the overlying variegated sandstone, there occurs a brick-red layer up to 10 metres thick. Shaw (Shaw, 1947), basing his opinion on the work of the Iraq Petroleum Company's geologists, refers to this sheet as a sill, perhaps interpreting the red series as a product of contact metamorphism. Closer study leads to another interpretation, for this red layer is everywhere composed of gypseous clay and contains no sand grains at all. But as the overlying rocks are true Nubian Sandstones it is very difficult to explain such a red clay as a product of their metamorphism, and it seems much more likely that this clay represents an old basaltic soil. This conclusion is supported by the fact that the

same red clay appears at places within the basalt sheet itself. Furthermore, a thickness as great as that of the magmatic sheet itself seems inadmissibly large for a zone of contact metamorphism.

We obtain, therefore, a picture of successive outpourings of basalt ; deep weathering then transforming each exposed surface into a red clayey soil which is, in turn, covered by later flows.

On such an assumption it is easy to understand the observed smaller thickening of the basalts before their final disappearance to the east ; the fronts of the flows were situated there and the lavas piled up as cooling increased their viscosity. The much larger increase in thickness towards the western part of the cirque is due to different reasons : there we are nearing the original centres of eruption ; this is evidenced also by the increased number of feeder dykes of the same petrological composition which cut all the older rocks of that area.

This formation of a red basaltic soil is interesting from a palaeo-climatological point of view ; for notwithstanding the present large outcrops of this basalt there is nowhere to be found any trace of recent soil formation. Instead the area is covered to-day by a basalt hammada. The climate at the beginning of Lower Cretaceous time must therefore have been much more humid than that of to-day. This conclusion is in harmony with that drawn from the abundance of fossil plant remains within the lower part of the Lower Cretaceous Nubian Sandstone throughout the whole Negev.

3. *Age of the Magmatic Activity.*

It is a conspicuous fact that whereas the whole sequence of Triassic and Jurassic rocks exposed in Wadi Raman shows an abundance of magmatic phenomena, no magmatic rocks have been found higher than the Main Basalt sheet. The Lower Cretaceous is therefore the probable upper limit of magmatic activity in the area.

On the other hand, no rocks older than Triassic are exposed and so the whole magmatic activity is contained within the time interval between the lowermost Triassic and uppermost Jurassic. However, with the exception of the main basalt sheet the magmatism is intrusive throughout ; it therefore does not necessarily follow that the magmatic activity started during the Triassic. It appears more probable that most of these processes, if not all of them, happened only during the Jurassic ; the end of the Jurassic is, in fact, a period of well-known volcanic activity in the Lebanon. Yet the diversity of the magmatic manifestations, of rock types as well as of modes of intrusion, suggests on the other hand that more than one phase is represented in Wadi Raman. A more exact chronology must await the detailed study of the rock types involved.

4. *Comparison with Other Areas.*

The magmatic phenomena exposed in the Wadi Raman cirque cannot be followed beyond its confines ; outside it all the Jurassic and Triassic rocks are deeply buried beneath younger strata. The nearest outcrops of older Mesozoic rocks are the two cirques of Jebel Ureif, at a distance of 14 km. due south. Here rocks down to the Muschelkalk are again exposed and a parallel series of magmatic rocks is once more encountered.

Further south the nearest outcrops of Jurassic and older rocks occur only at Wadi Menaiwyeh and southwards to Eilat at the southernmost tip of the Negev ; no magmatic rocks younger than Pre-Cambrian have been found there.

35 km. farther north of Wadi Raman, rocks of the Upper Jurassic age are again encountered in the Hathira cirque, but there are no traces of magmatic activity.

West of Wadi Raman, Triassic rocks are found in the cirque of A'raf en Na'ja, in the Eastern Sinai, 30 km. south-west of Wadi Raman ; but here again without any magmatic rocks being present.

The general conclusion may therefore be drawn that the Jurassic, and perhaps also the Triassic, were times of pronounced and varied magmatic activity, mostly of a hypabyssal nature.

Only at the end of the Jurassic did the magma give rise also to extrusive manifestations. The large volume of outpoured lavas evidently exhausted the magmatic reserves. The whole of this activity was geographically restricted to the central Negev area.

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Department of Geology,
The Hebrew University,
Jerusalem.

AIR-PHOTOGRAPH OF THE RAMAN-LACCOLITH.

Dark center: Laccolith. Surrounding white bands: Triassic Gypsum Series.
Scale 1 : 2,0000.

To face p. 140.

A Quartz Vein System in the Moine Series near Melness, A'Mhoine, North Sutherland, and its Tectonic Significance

By GILBERT WILSON.

(PLATE V)

ABSTRACT

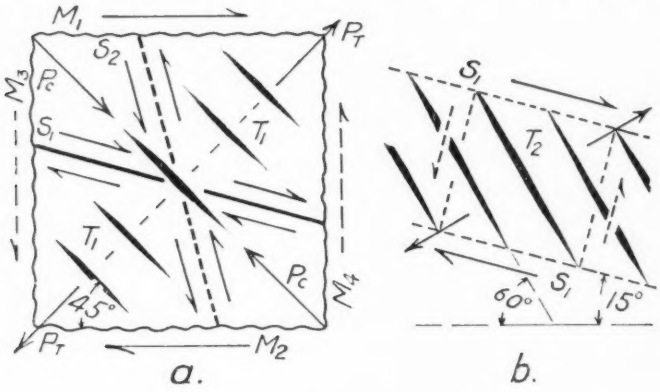
Kinematic analysis of tension gashes in an exposure of the Moine Series indicates that the fractures resulted from a tectonic movement directed from north to south, unrelated to that responsible for the nearby Caledonian Moine Thrust.

VEINLETS, gashes, and irregularly shaped masses of quartz abound in the Moine Series of Scotland, as they do in many other metamorphic terrains. In some parts of the region the larger and more continuous veins represent the outer fringes of big injection complexes (Read, 1931), but the ubiquitous smaller quartz lenticles and patches are for the most part segregation veins formed during the folding and metamorphism of the Series. Many of these veinlets follow the bedding or foliation of the country-rocks, but others cut across these structural planes in various directions. Those segregations which formed after the movements had ceased are commonly plane structures ; whereas those formed during tectonic episodes are broken, twisted, and rolled in conformity with the deformation of their host-rocks. Veinlets which developed late in the movement history of the rocks are obviously less deformed than those of early formation. Only rarely, however, can one find undeformed veins arranged in a pattern which has been controlled by the tectonic movements. Where such systems are recognizable they may be analysed, and a kinematic, or even a dynamic interpretation may be drawn from the visible structures.

A vein system of this class whose interpretation rests on simple mechanical principles is exposed on the west side of the Kyle of Tongue in North Sutherland (Geol. Surv. Scotland, Sheet 114). This structure is contained in a single outcrop, the more pertinent part of which is shown in the accompanying photograph, Plate V. It lies between the shore of the Kyle of Tongue and the road from Tongue to Melness and Loch Eriboll, about 500 yards south of the ferry across the Kyle, and is clearly visible from the road.

The exposure is formed of semi-pelitic Moine schist whose foliation dips easterly at about 20° and is probably parallel to the original planes of stratification. The quartz-filled gashes shown in Plate V are exposed in true profile on a steeply dipping joint surface which is at right angles to the local fold plunge and to the lineation. The gashes and veinlets

strike N. 76° E. and dip south. They can be divided into two groups : those which dip at about 45° and are mainly long and thin, indicated by T_1 in Text-fig. 1*a* ; and those which are short and stumpy and dip at angles between 55° and 90°, T_2 in Text-fig. 1*b*. A few veins are intermediate between these two groups. The steeply dipping gashes (T_2) lie *en echelon* within zones which also dip southerly, at inclinations between 12° and 20°, as indicated by S_1 in Text-fig. 1*a* and *b*. These zones, which are obliquely crossed by the quartz gashes, are similar to gently dipping ladder veins, to fracture patterns observed by Gilbert



TEXT-FIG. 1*a* and 1*b*.—Movement and stress analysis of the system of quartz veinlets illustrated in Plate V.

M_1 to M_4 : Couples resulting from external (tectonic) rock movements.
P_C, P_T : Principal stresses formed by the couples.
S_1, S_2 : Directions of maximum shear.
T_1, T_2 : Tension fractures now seen as quartz-filled veinlets.

(1928, fig. 2, p. 13) on the ground surface overlying the San Andreas Fault, and to the "feather joints" discussed by E. Cloos (1932). They are also closely comparable to the shear-zones with tension gashes described by the late Dr. V. E. Shainin (1950) ; and analogous structures associated with normal fault-zones at Tintagel have been illustrated by the present writer (Wilson, 1951, fig. 13, p. 424). Such fracture zones are therefore well recognized structural phenomena, and the mechanism of their formation is clearly understood. The short stumpy gashes (T_2) result from tensional stress developed in the rock by shearing forces acting parallel to the sides of the zones in which they lie ; that is, by the shearing couple (S_1–S_1) in Text-fig. 1*b*, and in the inset on Plate V.

The shear-zones in which these steeply inclined tension gashes

lie dip at about 15°. Theoretically they should be accompanied by complementary shear-planes, but the latter have not developed. They have, however, been inserted in Text-fig. 1*a* for completeness and are lettered S_2.

Tensional fractures (T_1) bisecting the lesser angle between the two directions of shear (S_1 and S_2) are represented in the rock face by the slender quartz veinlets which dip south at 45°. The fracture system is illustrated diagrammatically in Text-fig. 1*a*, the directions of the maximum and minimum principal stresses being indicated by P_C and P_T, which represent compressive and tensional directions respectively.

The structure under discussion is almost a replica of that obtained experimentally by Riedel (1929) in soft clay deformed by shear in directions corresponding to M_1 and M_2 in Text-fig. 1*a*. The application of such a shearing couple to the rock-mass would naturally invoke the action of an opposed couple of similar magnitude—M_3 and M_4—to prevent the rotation of the whole system. In Riedel's experiment the size of the angle which corresponded to that between the line of the applied shear (M_1–M_2) and the shear-plane (S_1) was 12° to 17°. Blyth (1950, p. 411) found in the sheared porphyry dykes of Galloway that this angle varied from small values up to 20°. An angle of about 12° between the direction of shearing movement and the resulting shear fractures was obtained when a block of limestone was deformed by shear in the Geologic Laboratory, University of Wisconsin, U.S.A. (Leith, 1923, fig. 11B, p. 37; also shown in Wilson, 1946, fig. 52, p. 288). The directions of shear, now represented by zones containing steeply dipping quartz-filled fractures make angles which average 15° with the horizontal trace of the foliation-planes on the rock-face in the exposure being considered. These planes, whether they be primary bedding or secondary schistosity, or both, are the surfaces along which the tectonic movements responsible for the structures described acted.

Although it is often unwise to attempt to deduce the distribution of forces responsible for observed geological structures, the present vein system is one in which the visible effect clearly indicates the cause. The quartz-filled fractures obviously result from the action of a couple (M_1–M_2) which developed by the translation of the upper beds over the lower ones towards the right (Plate V, and in Text-fig. 1*a*), that is, towards S. 15° E. Such a sense of movement is in accord with the directions of plunge and of the overturning of folds at Melness, some two miles further north, and also near Tongue about a mile and a half to the south-east across the Kyle.

This south-south-eastward direction of movement shows no relationship to the Caledonian thrusting on the other side of A'Mhoine, some five miles away to the west. It does, however, agree with that invoked

by Coles Phillips (1937) to account for the micro-fabric which he observed in the neighbouring Moinian rocks. It is clear therefore that the interpretation of the field evidence seen on this rock-face supports Coles Phillips' argument, based on " Gefüge ", that the Moine lineation in this area is in " *b* " and not in " *a* ".

The writer gratefully acknowledges that the expenses of field-work were defrayed by a grant from the Central Research Fund of the University of London. He also wishes to thank Professor David Williams, Dr. F. G. H. Blyth, and Mr. G. S. Sweeting who have kindly read through the typescript of this paper and made several helpful suggestions.

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DEPARTMENT OF GEOLOGY,
IMPERIAL COLLEGE,
LONDON, S.W. 7.

EXPLANATION OF PLATE V

Quartz-filled fractures in Moine Schist, 500 yards south of the ferry across the Kyle of Tongue. The scale is three feet long. Photograph looking towards the east.

QUARTZ FILLED FRACTURES IN MOINE SCHIST.

On a New Chrome-Garnet

By Sir Lewis Leigh Fermor

Abstract

The name *hanléite* is proposed for a magnesia-chrome garnet from Hanlé, Rupshu, Kashmir.

SOME years ago, in a paper entitled "Garnets and Their Role in Nature" (*Indian Assoc. for the Cultivation of Science*, Special Publication No. VI, Calcutta, 1938, p. 8), based on a series of three lectures on garnets, I pointed out that on the modern views of the atomic structure of garnet, in accordance with which the unit cell contains eight of the standard "molecules" of composition $R''_3R'''_2(SiO_4)_3$, we must accept the theoretical possibility of the existence of 16 sub-species of garnet, instead of the conventional six. These 16 comprised combinations of each of the four protoxides CaO, MgO, FeO, and MnO, with each of the four sesquioxides Al_2O_3, Fe_2O_3, Mn_2O_3, and Cr_2O_3. Of these possibilities the standard six comprise the four alumina garnets, grossularite, pyrope, almandite, and spessartite, one ferric garnet (andradite), and one chromic garnet (uvarovite), all well known. In my paper I list names for the three remaining ferric garnets, namely khoharite (magnesia), skiagite (ferrous), and calderite (manganous): and for one of the manganic garnets, namely blythite (manganous). This left six garnets still to be discovered, namely three manganic and three chromic garnets.

Recently, whilst delving into our Indian records, I found that one of the remaining chromic garnets had been discovered many years ago, though this had not been realized.

After an expedition with Stoliczka to the North-Western Himalaya in 1864, F. R. Mallet gave an account of the minerals collected (*Mem. Geol. Surv. Ind.*, v, 1866, pp. 153–172). Near the Hanlé Monastery, in Rupshu, Kashmir, Mallet found loose blocks of chromite. He did not observe this mineral *in situ*, but had no doubt that the blocks had been derived from the serpentinous rocks forming the hills on either side of the Rupshu-chu (river). We must now quote Mallet (loc. cit., p. 167):—

"Some specimens of the chromic iron are traversed by extremely thin seams of another chromic mineral, which outwardly much resembles Ouvarovite, but differs from it in composition. The chromate of iron has a slight tendency to break along these seams, both sides of which are then seen coated with very minute crystals of a brilliant emerald green colour. Viewed under the microscope the faces of the crystals appear to resemble those of a rhombic dodecahedron. This is the form of Ouvarovite which also resembles the mineral in question in its action before the blowpipe. Both are found with chromic iron. Ouvarovite, however, differs considerably in composition and also in

hardness ; (*a*) is an analysis of it by Komonen, (*b*) one of the mineral in question by Mr. Tween.

(*a*)		(*b*)	
Silica	37·11	Silica	41·2
Oxide of chrome	22·54	Oxide of chrome	33·5
Alumina	5·88	Alumina, Oxide of Iron, Magnesia	24·2
Protoxide of Iron	2·44		
Magnesia	1·10		
Lime	30·34		
Water	1·01	Water	1·1

In Ouvarovite the alumina replaces part of the chrome, the iron and magnesia replacing part of the lime. In (*b*) there is no lime, but the quantity of iron and magnesia is much greater. With regard also to the analysis (*b*) it should be mentioned that the quantity of the mineral available for examination was so extremely minute as to render a quantitative determination very uncertain."

Mallet later summarized this information in his Mineralogy (*Manual of the Geology of India*, part iv, 1887, p. 91) under the heading chrome-garnet ; but he omitted the analysis.

Although the amount of the mineral available for examination was so small Mallet was clear on one point, namely that this green chrome-garnet contained no lime, and instead a much greater amount of iron and magnesia than is present in uvarovite. The mineral could not, therefore, be uvarovite, however much it resembled it outwardly. The garnet was in fact an iron-magnesia-chrome garnet, in which the relative amounts of iron and magnesia were unknown. Tween's analysis, although it was made on such a minute amount of material, is obviously that of a garnet, even though the analyst has grouped alumina with the oxide of iron and magnesia, and even though he has not determined the state of oxidation of the iron, as of course he could not on the small amount of material available. In view of the large proportion of chromic oxide, the amount of alumina must have been trivial, whilst the oxide of iron must have been mainly the protoxide. Neglecting the alumina, we can compare Tween's analysis with the composition of uvarovite and of the theoretically possible magnesia-chrome and ferrous-chrome garnets :—

	Uvarovite.	*Hanlé garnet.*	$3MgO.Cr_2O_3.3SiO_2$.	$3FeO.Cr_2O_3.3SiO_2$.
SiO_2	35·9	41·2	39·8	32·8
Cr_2O_3	30·6	33·5	33·6	27·7
CaO	33·5	—	—	—
FeO	—	24·2	—	39·4
MgO	—		26·5	—
H_2O	—	1·1	—	—
	100·0	100·0	99·9	99·9

From this comparison it will be seen that although Tween has given no indication of the relative amounts of ferrous oxide and magnesia, yet the proportions of the three sets of oxides, silica, sesquioxide, and protoxides, in the Hanlé garnet, are much closer to those of a magnesia-chrome than of an iron-chrome garnet. Hence we can perhaps safely assume that the Hanlé garnet contains at least a considerable proportion of the magnesia-chrome garnet " molecule ".

If we may on this slender basis venture to give a name to the magnesia-chrome garnet " molecule " it should be *hanléite* after the Hanlé Monastery. Probably the Hanlé garnet, when analysed on an adequate quantity, will prove to be a mixture of the magnesia and iron chrome garnets, with the former predominating.

Last autumn I wrote to Dr. West, as Director of the Geological Survey of India, to ask if Mallet's specimens could be found, and if so subjected to further examination. The reply was that no trace of the Hanlé specimens could be found. Unfortunately Hanlé is in an inaccessible part of the Himalaya, and is not likely to be visited again unless by a special expedition.

24 Durdham Park,
Bristol, 6.

Notes on the Species and Subspecies in Palaeontology

By W. S. McKerrow

Abstract

The view is put forward that, as any subdivisions of an evolving plexus must be arbitrary, the existing binomial system of nomenclature should continue to be applied to morphological species in palaeontology, rather than be replaced by any other arbitrary system which could not be applied generally.

The Species

RECENTLY some authors, e.g. Haldane (1949) and Newell (1947), have re-stated that the term " species " should only be applied to whole populations, adding that two such species might conveniently be distinguished if the means of a measureable character for samples of the two populations were more than 4σ apart (where σ is the standard deviation of one sample). That is, it is proposed that standardized criteria should be used to delimit successive species, which would normally consist of very different groupings than are covered by the present intergrading morphological species of many authors.

Fossil populations change gradually (both laterally and vertically), and some arbitrary criteria must inevitably be employed to demarcate the smaller systematic categories. The present system of nomenclature can be adapted satisfactorily to the palaeontologist's needs ; and any drastic revision of nomenclatural principles in order to substitute one arbitrary system for another, equally arbitrary, would not appear to be worth while.

The wider and more active appreciation of the fact that the great majority of the specific names already in use cover only morphological species would seem to the writer to be the easiest and most satisfactory solution to this problem. Forms similar to but not identical with the named types can be prefixed " aff." or " cf.", as was proposed by Trueman (1924) and used so successfully by Davies and Trueman (1927). The consideration of several characters in defining the forms to be covered by one specific name is likely to be more useful than a diagnosis depending solely on the measurements of one character.

Authors have always been faced with the temptation of erecting new names ; but this temptation would be greatly reduced if it can be understood that all specific names represent arbitrarily selected points in a plexus, and that no purpose is served in creating more of these described points than is useful (to either the evolutionist or the stratigrapher). Moreover, the number of such names that are useful to the specialist is in the great majority of cases very much greater than the general reader would need, but (to quote Trueman, 1924) " the better

known specific names can always be used in their non-restricted sense, provided it is made clear that they are so used ".

The Subspecies

Sylvester-Bradley (1951) has recently summed up similar opinions to those of Haldane and Newell on the definition of a sub-species. He distinguishes between geographical and chronological sub-species. His definition of the former (that they are isolated populations) is not in complete accord with modern biological usage. If two ends of a long chain of populations differ sufficiently (by clinal selection) they can be called different sub-species as they retain their identity in spite of gene flow.

Sylvester-Bradley's definition of a chronological sub-species is of doubtful practical value because he again neglects lateral changes in variation. He refers to Burma (1948), who points out that the mean of a population cannot be determined more accurately than to within $M \pm 2\sigma_M$, i.e. to within twice its standard error. Sylvester-Bradley then selects this as the basis of his chronological subspecies, i.e. his unit is the smallest difference that is statistically significant. He implies that each such subspecies should be designated by a different name. With more collecting, and a resultant increase in the size of samples, his units would automatically decrease in scope, and literature would become burdened with a constant revision of nomenclature and an ever increasing multitude of names.

Work recently carried out by the writer in the Ornithellids of the Fuller's Earth Rock (not yet published), has shown that samples of this brachiopod community from localities a few miles apart, but from the same horizon, can possess several characters which have their means significantly different. Therefore, to apply Sylvester-Bradley's method of distinguishing chronological subspecies an author would have to take into account the means and standard deviations of samples, not merely from one locality but from over the whole area of distribution of an interbreeding community (incorporating all the lateral changes in variation); and in practice this is hardly ever possible because of erosion, burial, etc. Moreover, in palaeontology, provision must be made for incompletely known groups, and it is imperative to have a system of nomenclature which can be progressively adapted as fuller information (including statistical data) becomes available.

Nomenclature

For these reasons it would seem to the writer that specific names should continue to be applied to morphological species in palaeontology. Such a practice has the advantages that—

(1) no drastic revision of nomenclature is necessary,

(2) morphological species may be defined by as many characters as is convenient, and do not depend on the measurements of only one character,

(3) the same system of nomenclature can be used for all fossil groups, regardless of how many specimens are available.

The recognition of geographical subspecies may be useful in some instances, but the use of the chronological subspecies as defined by Sylvester-Bradley does not confer the above advantages, and in addition depends on the collection of forms from over a very wide area which is not normally accessible.

Wood and Barnard (1946) suggest the use of a quadrinomial system designating the genus, species, variety, and cline of each form. This is possibly useful in the study of a group from one locality and horizon, where the variation is restricted along definite lines (as is the case with the genus *Ophthalmidium* from the base of the Upper Lias at Byfield, Northamptonshire). Such a system of nomenclature, however, must have arbitrary divisions when the group studied extends through many horizons ; and it would seem to the writer that as an arbitrary system is inevitable it should be as simple as possible, i.e. binomial.

Conclusions

In any fossil group the variants characteristic of a given locality and horizon can be portrayed graphically or by means of pictographs and related distribution scatters (as first developed by Leitch, 1936) ; this is, in fact, done by Wood and Barnard for *Ophthalmidium*. But neither each variant nor each different population need necessarily be designated by a separate name (specific or subspecific or varietal).

The writer considers that existing specific names should be retained to cover forms similar to the described types. It is *useful* to have names available to designate the chief morphological forms in any widely varying community ; and as the existing binomial system can be adapted to the present needs it would appear purposeless to substitute any other system which cannot be applied generally.

Acknowledgments

Thanks are due to Sir Arthur Trueman, Professor T. Neville George, and Dr. T. Whitworth for helpful suggestions and criticism, but it should not be supposed that they necessarily agree with all the views here expressed. The author has also discussed the neontologist's views of these problems with Dr. A. J. Cain.

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DEPARTMENT OF GEOLOGY AND MINERALOGY,
UNIVERSITY MUSEUM,
OXFORD.

CORRESPONDENCE

ZOOLOGICAL NOMENCLATURE

SIR,—At its meeting held in Paris in 1948, the Thirteenth International Congress of Zoology decided that a number of general problems of great importance involving the text of the International Code of Zoological Nomenclature should be brought forward for decision at the next (Fourteenth) International Congress of Zoology at its meeting to be held in Copenhagen in 1953. The Paris Congress further decided that, as a preliminary to the submission of these problems to the Copenhagen Congress, the Secretary to the International Commission on Zoological Nomenclature should confer with interested specialists and, having done so, should submit comprehensive Reports, with recommendations.

I have accordingly prepared papers on each of the problems remitted to me for Report, setting out the issues on which, as it appears to me, the Copenhagen Congress will need to take decisions. These papers also include a number of suggestions based upon such preliminary consultations as have already been held.

The subjects dealt with in the papers referred to above are the following :—

(1) Emendation of zoological names : proposed substitution for Article 19 of simple clear-cut rules capable of being easily applied (Commission's reference Z.N.(S.) 356) ;

(2) Clarification and amplification of the rules relating to the naming of families and lower categories of suprageneric rank (Commission's reference Z.N.(S.) 357) ;

(3) Proposed introduction of rules for regulating the naming of Orders and higher taxonomic categories (Commission's reference Z.N.(S.) 360 ;

(4) Species to be accepted as the type species of a nominal genus, the name of which was published in a generic synonymy, if names so published are to be treated as possessing nomenclatorial availability (Z.N.(S.) 387) ;

(5) Application to be given to a trivial name which, when first published, was applied to a particular species or specimen but which is stated also to be a substitute name for some previously published name (Commission's reference Z.N.(S.) 361) ;

(6) Neotypes : question whether this class of type specimen should be officially recognized and, if so, under what conditions (Commission reference Z.N.(S.) 358) ;

(7) The means to be devised for securing stability in zoological nomenclature (Commission's reference Z.N.(S.) 359) .

A special volume (vol. 7) of the *Bulletin of Zoological Nomenclature* has been allotted for the publication of the foregoing papers : parts 1/2 containing

the first instalment of the above papers will be published on 25th February, 1952; the whole of the remainder of the volume will be published within the next six weeks.

The object of the present notice is to draw the attention of zoologists and palaeontologists to the arrangements being made for the consideration of these problems by the Copenhagen Congress next year, and to express the hope that Nomenclature Committees of museums and other scientific institutions and also as many individual specialists as possible will answer the questions specifically asked in the concluding paragraph in each of the seven papers enumerated above regarding the action which, in their opinion, it is desirable that the Copenhagen Congress should take on each of the important problems involved. It is hoped that there will be a wide and representative response to the present appeal, so that the proposals to be submitted to the Copenhagen Congress will command the widest possible measure of support among the general body of zoologists and palaeontologists

Nomenclature Committees and individual specialists who respond to this appeal are asked to observe the following procedure when furnishing statements of their views: (1) Where comments are furnished on two or more of the general problems enumerated above, the comments furnished on each of those problems should be on separate sheets of paper. (2) Every comment furnished should be clearly marked with the Commission's Reference Number as indicated in the list given above. (3) Comments should be typewritten, on one side of the paper only, with wide margins, and should be furnished in duplicate. (4) Comments should be dispatched as soon as possible, and should in any case reach me not later than 31st July, 1952.

FRANCIS HEMMING,
Secretary to the International Commission on Zoological Nomenclature.

28 PARK VILLAGE EAST,
REGENT'S PARK,
LONDON, N.W. 1.
20th February, 1952.

ACCURACY IN GEOLOGICAL LOCALITIES

SIR,—The late Dr. Rastall wrote on this subject in this magazine in 1949 (lxxxvi, 110–12) and Mr. Percy Evans insisted on the value of the National Grid in 1948 (lxxxv, 242–3). I am at present conducting a census of Sarsens and Puddingstones in the Chiltern area, and find National Grid references quite indispensable.

My immediate object in writing is, however, to put on record two striking examples of inaccurate locality that have come to my notice.

For many years Diss, in Norfolk, figured as a locality for Red Crag echinids, although no Red Crag is mapped anywhere near. I owe belated thanks to Mr. L. Bairstow for solving the mystery. It seems that the echinids were presented to the Jermyn St. Museum by a collector whose address was at Diss. I might be the innocent agent of a similar mistake, for I once received a letter of thanks from the Geological Survey for a gift of Rhaxella-chert "from Arngrove, Amersham", whereas the locality Arngrove is some 24 miles from Amersham.

Cossmann, in his *Essais de Paléoconchologie Comparée* (vi, 17) stated that the remarkable Miocene gastropod *Pereiraia gervaisi* occurred at "Ivandel près Bartelmae dans l'Ukraine", but Ukraine is a slip for U(nter) Krain, otherwise Lower Carniola (now the Jugoslav province of Slovenia) at least 500 miles from Ukraine.

A. MORLEY DAVIES.

"ARNGROVE,"
STATION ROAD,
AMERSHAM, BUCKS.
20th February, 1952.

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